THE SIGNIFICANCE OF WELD DEFECTS - A MORE RATIONAL ASSESSMENT

Jerry Melvin Monroe

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by

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ABSTRACT

This thesis surveys the concepts and analysis techniques available for more rational assessment of the significance of weld defects. In addition, a systems approach to brittle fracture prevention that can be practically applied to welded structures is developed.

The need for analysis techniques that provide a more rational and rigorous means of assessing the significance of weld defects is shown to be met by the use of fracture mechanics technology. Through the use of fracture mechanics analysis techniques, the size of the maximum allowable weld defect can be established and used as an acceptance criterion for weld defects. Critical flaw sizes can also be determined under conditions of fatigue and environment-induced crack growth.

In the systems-type approach to the prevention of brittle fracture, analysis techniques are employed that consider the interaction between material characteristics, design, fabrication, inspection and operational requirements of the welded structure.

While the use of fracture mechanics concepts in the areas of weld defect assessment and brittle fracture prevention is expanding, additional work and development is required before they will find wide application to varying types of welded structures.

Thesis Supervisor: Koichi Masubuchi
Title: Professor of Ocean Engineering and Materials Science

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PART I

BACKGROUND AND STATE-OF-THE-ART

CHAPTER 1

INTRODUCTION

Weld defects are a fact of life. From the time when the first welded structure was fabricated to the present day, investigators have continued to pursue ways to eliminate defects, to develop techniques for defect detection, and to find methods of assessing their significance.

Weld defects are important because, under the right set of conditions, they can be directly responsible for the failure of a welded structure. The modes of failure most significantly influenced by weld defects are brittle fracture and fatigue.

Brittle fracture is characterized by a fracture which occurs suddenly, without warning. The grains at the tip of the defect are subjected to enormous stress peaks. Grains try to equalize the stress by distributing it over their neighbors. If general local yielding occurs, the magnitude of the peak stress around the imperfection is effectively reduced and the flaw becomes insignificant. However, under some conditions, and especially at low temperatures, steel shows a special resistance to yielding. It appears that this aversion to yielding allows high stress peaks to build up too quickly to be relaxed by slip. Deformation twinning and other violent processes result, which break the metal and initiate a brittle crack. Once brittle fracture is initiated, very rapid propagation occurs leading to a

structure whose integrity is severely impared, or to the catastrophic failure of the entire structure. Catastrophic failure can occur in large welded structures because they are monolithic, which permits a fracture to propagate beyond a single plate.

This type of failure evolves with no noticeable plastic deformation preceeding or accompanying the fracture. It occurs at nominal stresses well below the yield strength of the material.

Fatigue represents a situation where a small, insignificant weld flaw can grow to a size large enough to initiate brittle fracture. Thus, a structure under cyclic loading conditions can experience failure resulting from smaller initial weld defects at lower applied stress levels than a similar structure which experiences static load conditions.

In addition to introducing weld defects into the structure, the very act of welding can be detrimental in other respects. It sets up high local stresses and can damage the fracture resistance of the base metal. These conditions can combine to make the presence of a weld defect even more dangerous.

Clearly, the occurrence of brittle fracture must be avoided by whatever means possible. This problem takes on even more urgency with the new high strength metals. The brittle fracture phenomenon is more critical for the high strength materials because as the strength increases, the resistance to fracture of the material is reduced.

One method of preventing the occurrence of brittle fracture has rested on setting limits on the sizes and types of defects allowed in the weld. Weldments containing defects are then accepted or rejected based upon the application of these standards. Unfortunately, current weld defect acceptance standards lack any significant ties with scientific facts. They merely attempt to define the normal limits for practical welding. By adhering to these standards, the number of unnecessary repair welds has grown very rapidly. The situation is made even worse as the weld defect detection capabilities of non-destructive testing techniques is improved.

Obviously, there exists a need to employ concepts and analysis techniques that provide the designer and manufacturer with a more rational and rigorous means of assessing the significance of weld defects. Such concepts and analysis techniques do exist and need only to be implemented. The objective of this study is to survey these concepts and to present techniques that can be applied to obtain a more rational assessment of the significance of weld defects. The study will be carried out in the context of providing brittle fracture immunity for the welded structure.

The study is presented in two parts. Part I deals with a generalized discussion of the various areas involved in the assessment of the significance of weld defects, and presents the present state-of-the-art. Topics discussed

include weld defect types and characterization, current weld defect acceptance standards, weld defect assessment concepts, environmental considerations, and the utilization of fracture mechanics concepts for more rational weld defect assessment.

Part II attempts to bring the various factors presented in Part I together into a systems-type approach to the prevention of brittle fracture. The primary goal is to develop an approach which could be practically applied at all stages in the development and service of the structure. Numerical examples are included to demonstrate the analysis.

CHAPTER 2

WELD DEFECT CHARACTERIZATION

2.1 Weld Defect Types

It is a characteristic of welded joints that they are never completely defect free. The subject of defects in welded structures has been a matter of concern since the advent of the welding process. The causes of weld defects generally fall into one of five categories:[5]

1. Lack of welding know-how and experience
2. Welding process characteristics
3. Base metal defects or compositions
4. Material selection and properties
5. Welding environment (joint design, fit-up, temperature, support, etc.)

Some of the common weld defects resulting from the problems listed above include:[9,12,22,14]

Geometrical

1. Undercut and cavity
2. Overlap
3. Poor fit up - mismatch
4. Excess reinforcement
5. Stress concentrations in general
6. Nature of weld dressing

Metallurgical

1. Stress relief cracking
2. Hot cracking and microfissure

3. Cold cracking and delayed cracking
4. Strain-age cracking
5. Gas porosity
6. Lack of penetration
7. Lack of fusion
8. Microsegregation during cellular or dendritic growth
9. Embrittlement
10. Arc strikes
11. Entrapped weld spatter

Foreing Inclusion

1. Oxide films
2. Slag inclusions
3. Delaminations
4. Tungsten inclusions in GTA welds

In addition to these defects in the welded joint, all zones of diminished or insufficient ductility should also be considered as welding defects.(2)

The defects considered above were formed during the welding process or the post weld heat treatment and may sharpen and grow while the structure is in service. Other defects are formed in the course of the service life through the action of fatigue cracking, creep rupture, stress corrosion cracking, and irradiation embrittlement.(2)

2.2 Effects of Weld Defects

As is evident, the range of weld defects that can be produced is large and almost every type of defect has been

shown to be hazardous under one set of conditions or another. The presence of a defect can significantly reduce the strength of the welded structure under given circumstances.

For certain structures, geometrical factors may often be the primary consideration in establishing the soundness of the structure. In this case, other types of defects are relegated to a relatively minor role.

In visualizing the metallurgical aspects of defects and welding, the diagram presented by McEvily[9] is useful. Here one can see the effect of a change in metallurgical character on the fracture behavior of ferrous materials. McEvily's diagram is shown in Figure 2-1. The figure is a three-dimensional plot with the axes being stress, the reciprocal of the square root of the grain size, and temperature. Region ABC is a surface which is the locus of fracture which occurs when the applied stress reaches the yield stress. For temperature and grain size combinations to the right of line BC, failure occurs above yield and is initiated by either cleavage or shear. The important factor to note is that for an increase in grain size, as in the heat affected zone of a weld, not only is the yield strength lowered but the potential for brittle fracture is increased. The presence of a flaw or notch will raise the local yield stress because of plastic constraint with the result that brittle transition temperature is increased. An increase in transition temperature will also result from increasing impurity levels of the weld. Strain aging, irradiation, and increase

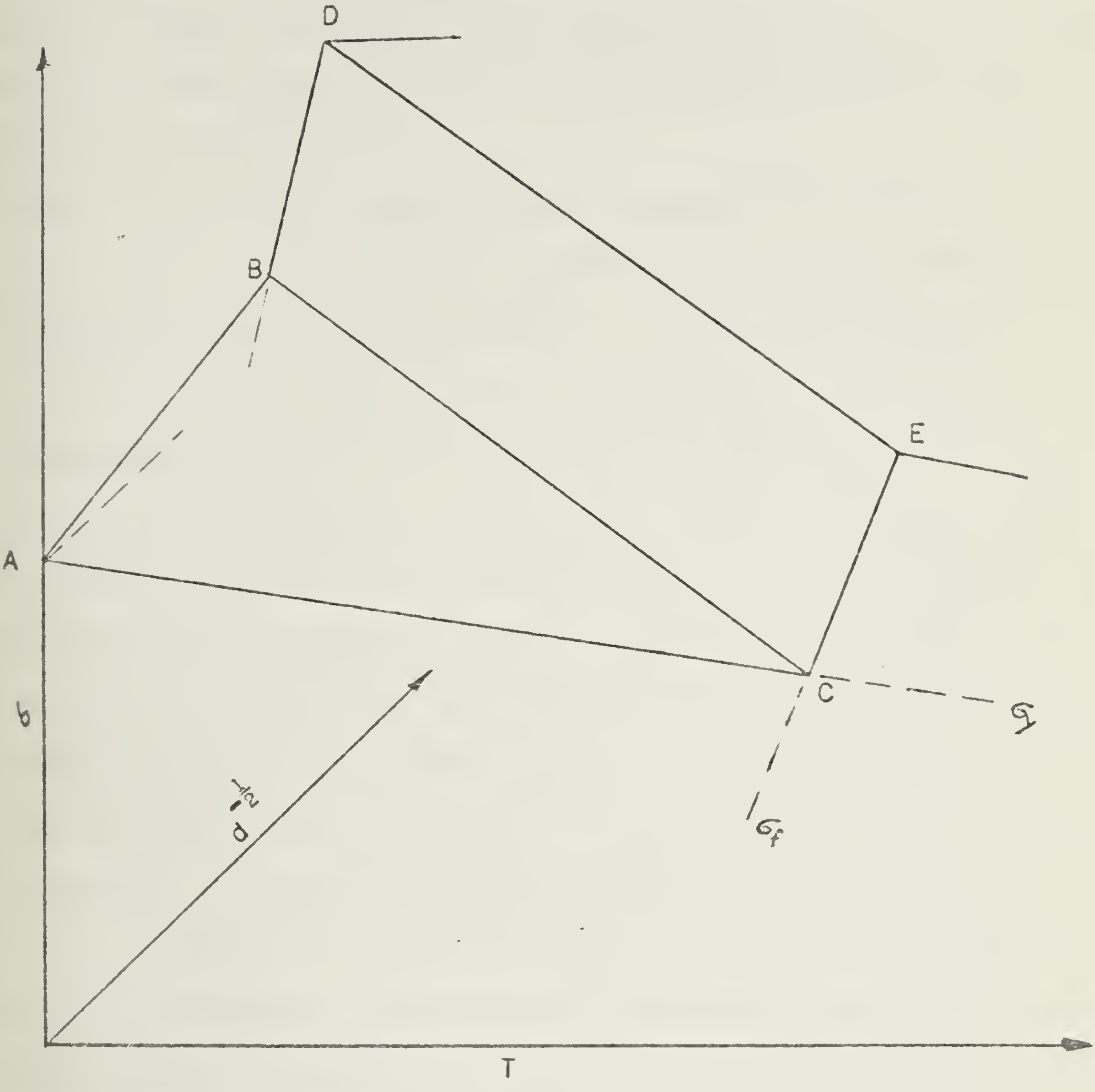


FIGURE 2-1. Three dimensional stress (σ), temperature (T), and reciprocal of the square root of grain size ($d^{-\frac{1}{2}}$) plot. Cleavage initiated fractures to right of DE. ABC is a surface upon which brittle fracture occures when the applied stress reaches the yield stress.

in strain rate will all raise the yield stress curve with a resultant increase in the tendency for brittle fracture.[9]

Hot cracking due to microsegregation, cold cracking, incomplete fusion, porosity, shrinkage cavities, and arc strikes can each lower fracture stress (σ_f) and reduce the reliability of the weld.[9]

Because of fatigue implications, undercut and other defects which can appear on the surface may be more harmful than defects within the weld deposit. As a matter of fact, when a defect breaks the surface, it can be twice as serious as an embedded defect of the same size.[17] Figure 2-2[7] demonstrates the effect of crack location on the fatigue life of a pressure vessel made of HY-130 steel. Undercut itself is generally not considered harmful, unless the structure experiences very severe in-service fatigue conditions.[5]

Cracks are one of the most harmful of welding defects and, as such, have been the focus of much interest and experimentation. Cracking can occur either in the weld or base metal. Cracks are generally grouped into one of three classes, hot cracking, cold cracking and microfissuring. It is widely accepted that major cracks are harmful to the welded structure, whereas fissure and microfissure may not degrade the service life.

Because of the importance of cracks and the attention they have received, cracks and crack-like defects will receive principal consideration in this paper.

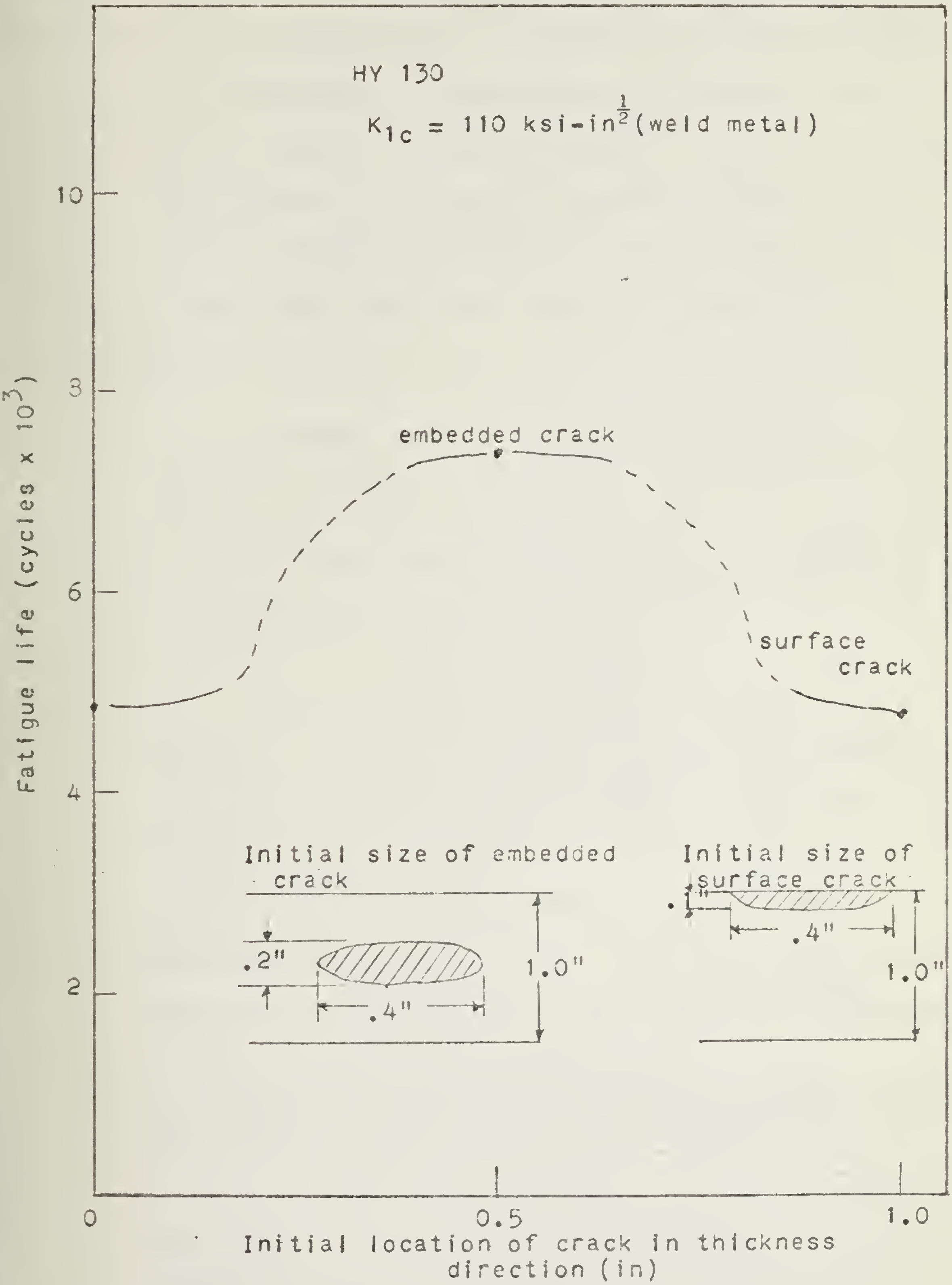


FIGURE 2-2. Effect of crack location on fatigue life.

Whatever the defect type, the degree to which the flaw increases the risk of failure by reducing the strength of the structure is influenced by the following factors:[8,29]

1. The nature of the loading conditions, i.e., static, impact, fatigue or creep. When a structure is subjected to impact or repeated loading, the effect of defects on the strength becomes more serious than when the structure is subjected to static loading.

2. The stress level at the point where the defect is located.

3. The lowest temperature to which the structure is subjected in service.

4. The properties of the material in which the defect is located. When the material is ductile, the reduction of strength is approximately proportional to the reduction of cross-sectional area. For less ductile materials, the effects of defects become more serious. When the material is brittle, the absolute size of a defect is important.

5. The nature and extent of defects. Sharp cracks that cause severe stress concentrations have a greater effect than do porosity or slag inclusions. The effect becomes more severe as the size and number of defects increase.

2.3 Defect Detection by Non-Destructive Testing

The realization that welds can contain a wide range of defects has precipitated great interest in developing non-destructive test techniques for defect detection. It is a fact, recognized by the designer, that the presence of defects can significantly reduce the strength of his structure. He has therefore come to rely on non-desctructive inspection as an acceptance criteria upon which to base a determination of the validity of the weld. These criteria take the form of limits on defects as specified in existing codes.

As will be seen later on, non-destructive testing has taken on an even more important role in providing detailed description and dimensional measurement information on defects, which is so essential to proper utilization of fracture mechanics analysis.

Ideally, a non-destructive test (NDT) technique should be able to detect all defects in a weld, and accurately determine the geometry, orientation and position of the defect. Obviously, it is not possible with existing NDT methods to meet such requirements.

In order to approach the ideal, there is an on-going effort to develop more accurate NDT methods. In addition to this, only the most skilled personnel are allowed to conduct the tests, and then, only under the correct examination conditions in accordance with established codes and standards. Various complementary inspection techniques are also employed on the same weld to achieve the maximum definition of existing defects.

Accurate knowledge of the sensitivity and reliability capabilities of major NDT inspection methods is meager.[22] Most of the current NDT work is centered on developing and improving equipment and standardizing inspection techniques.

The sensitivity of a NDT process is defined as: the ratio of the number of flaws that can be detected by an NDT process divided by the total number of flaws that actually exist in the part.[22] For example, if only 5 flaws are detected out of ten samples containing a flaw, the sensitivity is no greater than 50%. Table 2-1[22] lists a summary of selected detection sensitivities. These are estimates of the size of the smallest flaw that can be detected by a given process at least 90% of the time.

In order to use the flaw sizes given in Table 2-1 for design purposes, a determination must be made as to the probability of detecting a flaw at a given confidence level. Packman[22] shows that for a given NDT technique, the probability of detecting a flaw can be calculated using a Chi square (χ^2) distribution approximation of the binomial distribution. This can be expressed by the relationship:

$$nq = 1/2\ \chi_c^2 \text{ with } f = 2(x_o + 1) \qquad (2.1)$$

where χ_c^2 = the confidence limit fractile of the χ^2 distribution

f = the degrees of freedom

x_o = the number of flaws missed

TABLE 2-1. Selected detection sensitivities of NDT processes. (sensitivity greater than 90% no confidence limits)

TECHNIQUE	MATERIAL	SIZE (in)	COMMENTS
Visual	7075-T6511	0.03	Fatigue crack Magnification
Ultrasonics	"	0.25	Fatigue 50 MHZ .25" shear transducer
Penetrant	"	0.25	Fatigue No pre etch
X-ray	"	0.50	Fatigue
Visual	4330V	0.03	Fatigue crack Magnification
Ultrasonics	"	0.20	Fatigue crack .25" shear transducer
Penetrant	"	0.35	Fatigue No pre etch
Mag particle	"	0.30	Fatigue crack
Surface wave Ultrasonics	2219-T87	0.20	Fatigue crack
Penetrant	"	0.20	Fatigue crack
Eddy current	"	0.20	Fatigue crack
Shear wave Ultrasonics	"	0.25	Various configurations
X-ray	2219-T87 +welded	0.30	Fatigue crack
Delta Scan	D6AC	0.15	Induced flaws
Mag rubber	D6AC	0.035	Induced flaws
Delta wheel	2014Al	>0.01	Porosity
60° angle Ultrasonics	2014	>0.01	Porosity
X-ray	2014	>0.01	Porosity
Penetrant	7075-T6	0.075	Fatigue
Mag particle	D6AC	0.100	Fatigue

n = the total number of specimens examined

q = the upper confidence limit for the probability of failure detection

For illustrative purposes, Figure 2-3[22] shows the probability of detection at a 95% confidence limit as a function of the number of test inspection trials. From the figure, it can be seen that in order to have a 90% probability of detecting a flaw at a 95% confidence limit, the NDT method must be able to detect at least 29 flaws out of a given group of 30 specimens, all of which contain flaws within the given flaw size range.

Table 2-2[22] lists various NDT processes, along with the minimum flaw size of surface fatigue cracks that can be detected at the given confidence level.

Packman goes on to define the accuracy of the flaw size measurement as:

$$A_{NDT} = 1 - [(2a_{NDT} - 2a_{ACT})/2a_{ACT}] \tag{2.2}$$

In this expression,

A_{NDT} = the accuracy of the flaw measurement

$2a_{NDT}$ = the NDT estimate of the flaw size

$2a_{ACT}$ = the actual size of the flaw as measured on the fracture surface

Typical accuracy indexes for several NDT procedures are shown in Figure 2-4.[22]

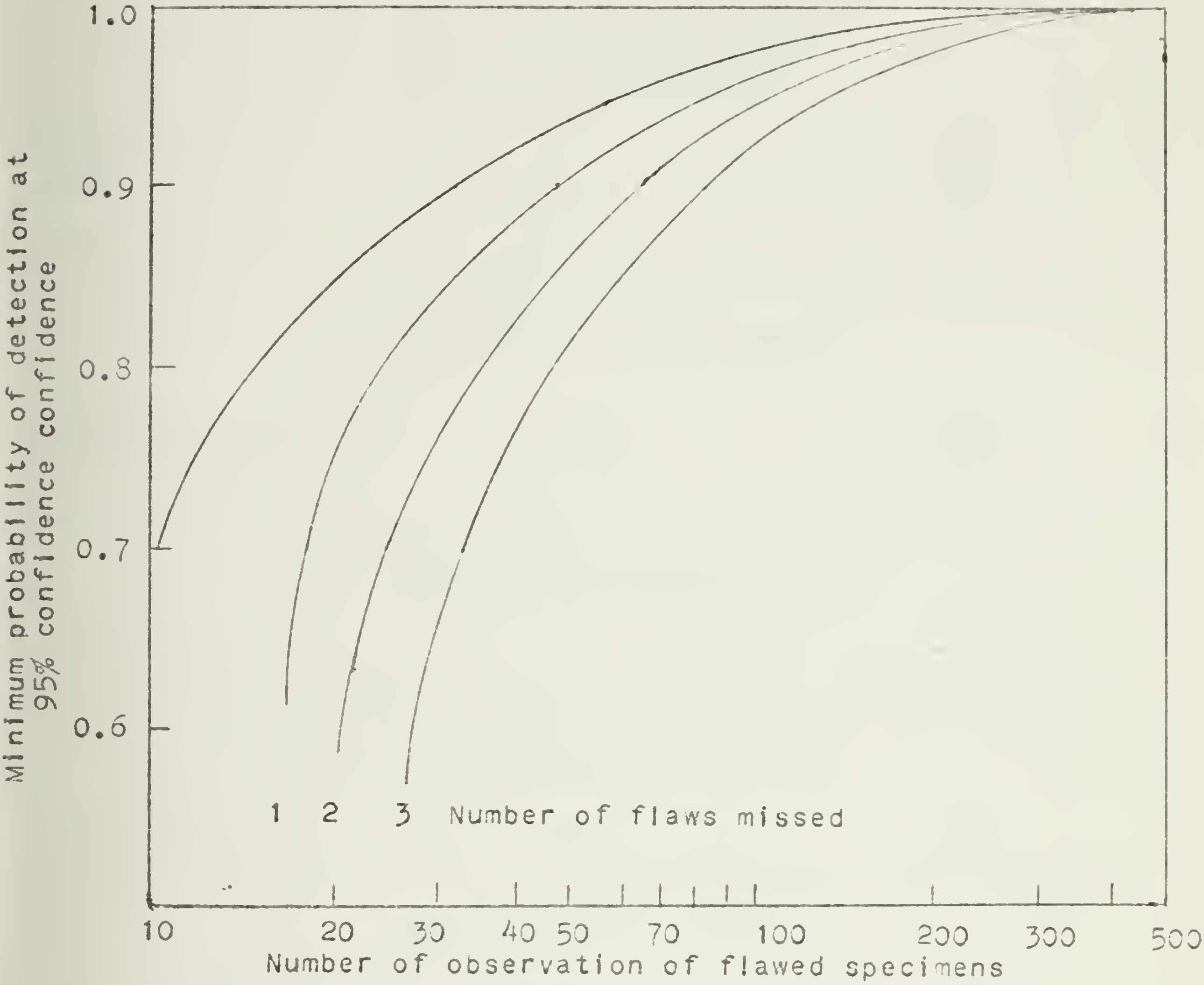


FIGURE 2-3. Plot of the minimum number of observations that must be made to ensure minimum probability of detection at 95% confidence.

TABLE 2-2. Flaw sizes detectable at known confidence limits (in.)

FLAW SIZE RANGE	PROB. OF DETECTION	CONFIDENCE LEVELS
	Mag Particle-HP-9 steel. MTL-I-6868 with 0.1 to 0.15 ml per 100 ml SO_2	
.030-0.75 (2a)	75%	95%
.076-.100 (2a)	90%	95%
.101-.150 (2a)	90%	95%
	P5F-2.5 penetrant system Ti6Al-4V 0.5 mil etch	
.030-.075 (2a)	90%	95%
.076-.100 (2a)	90%	95%
	Instaviz P5F 1.0 penetrant-alum. 0.5 mil etch	
.030-.075 (2a)	90%	95%
	P5F-1 penetrant-alum. RHR 65 or better 0.5 mil etch	
.076-.100 (2a)	90%	95%
	5MhZ 45° and 70° duplex inspection	
.030-.075 (2a)	90%	95%
.076-.100 (2a)	90%	95%
	Mag rubber double inspection	
.030-.050 (2a)	90%	95%

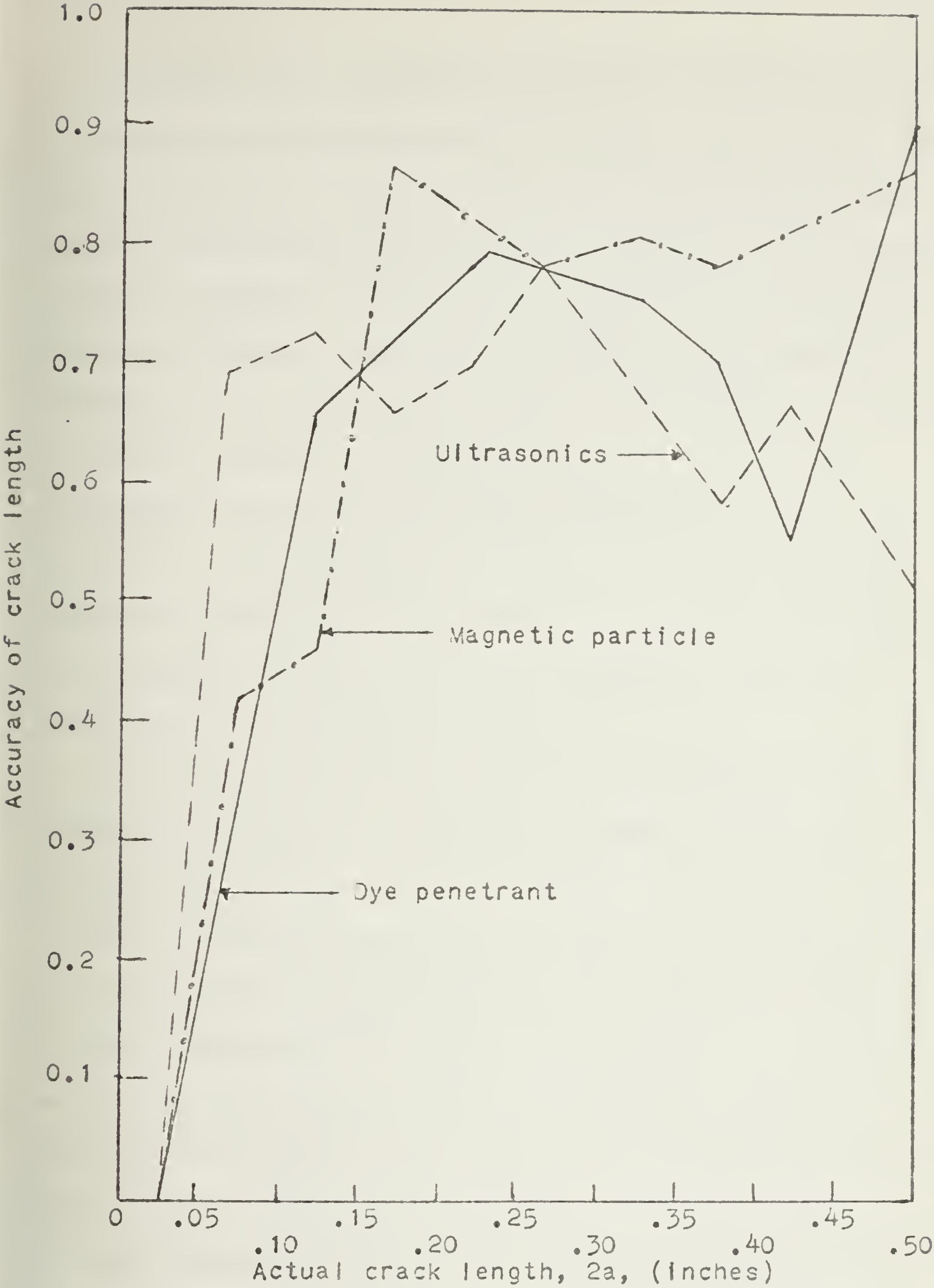


FIGURE 2-4. Accuracy of crack length indications by NDT in 4330 V modified steel specimens.

As previously mentioned, various NDT methods can be used in conjunction with each other to achieve the maximum flaw characterization. Internal defects can be located using either ultrasonic or radiographic techniques, while surface defects are usually located with magnetic particle or dye penetrant methods. Since radiography is only capable of providing a two-dimensional picture of an internal defect, ultrasonic inspection of the same flaw is helpful in accurately determining the depth and orientation of the defect with respect to the surface. Similarly, magnetic particle or dye penetrant inspection can reveal the length of a surface flaw, but ultrasonic techniques may be necessary to establish its depth.

One of the most commonly used NDT techniques for detection of weld defects is that of penetrating radiation. This includes X-ray, gamma ray and neutron radiography. Such radiation techniques are capable of detecting metallurgical flaws and defects whose dimensions are large with respect to the wall thickness.[22] X-ray sensitivity, for example, is usually given in terms of percent of wall thickness, standard sensitivities being on the order of 2% of the wall thickness. Thus, defects whose gross dimension is on the order of 2% of the thickness of the wall are theoretically detectable. Gamma radiography is usually less sensitive than X-ray, but because of higher penetrating power, it is extensively used for thick sections.

Recent radiographic techniques which have been developed include the radio penetrants and positron annihilation. The radio penetrant technique uses absorbed radioactive gasses to emit beta radiation, which are concentrated and detected in the vicinity of cracks and pores. Positron annihilation makes use of the fact that gamma photons resulting from positron annihilation are emitted more readily at loci of microstrain.[22]

Ultrasonic inspection techniques make use of high frequency sound waves to detect, locate and measure discontinuities in weldments. Recent ultrasonic work has indicated that the nature of the mismatch at the defect-base material interface has a significant influence on the amplitude of the reflected signals. If the acoustic mismatch between defect and base material is too small, insufficient signal is reflected at the interface to provide a reliable indication.[22]

Penetrant techniques are commonly used for detection of surface defects. The effectiveness of penetrant systems is dependent upon the ability of the penetrant to enter the defect, and, with the proper post-application treatment, re-emerge for visual inspection. Tables 2-1 and 2-2 show that penetrant systems can detect and measure extremely small cracks, provided the proper procedures have been followed.

Another promising method of non-destructive testing that has emerged recently, after extensive research and development, is acoustic emission (AE).[23] AE testing has found industrial application in detecting flaws through a

triangulation technique. It is also useful in providing early warning of impending failure, by using an emperical correlation between AE and stress intensity factor.[23]

In summary, Table 2-3[12] gives weld defect detection capabilities for various NDT techniques, and Table 2-4[12] gives typical quality characteristics appraisable by non-destructive testing.

TABLE 2-3. Weld Inspection by Non-Destructive Test Methods

	CRACKS	INCLUSIONS		POROS-ITY	LACK OF PENE-TRATION	LACK OF FUSION	LACK OF BOND	UNDER-CUT	ALLOY IDENTI-FICATION	ALLOY COMPOSITION		LEAKS	
		NON-METALLIC	METALLIC							MACRO	MICRO	LARGE	SMALL
Film Radiography	P	G	G	G	G	P	N	G	N	N	N	P	N
TV X-ray Fluoroscopy	G	G	G	G	G	G	N	G	N	N	N	P	N
Visual Methods	P-S	P-S	P-S	G-S	G-S	P-S	N	G	N	N	N	P	N
Magnetic Particle*	G-S	G-S	G-S	P	G-S	G-S	G-S	P	N	N	N	N	N
Liquid Penetrant	G-S	P-S	N	G-S	G-S	G-S	G-S	P	N	N	N	P	N
Sonic Leak Detector	N	N	N	N	N	N	N	N	N	N	N	G	N
Helium Leak Detector	N	N	N	N	N	N	N	N	N	N	N	G	G
Ultrasonic	G	P	N	P	G	G-P	G	P	N	N	N	N	N
Current-Potential	G-P S	N	N	N	G-P	G-P S	G-P	N	N	N	N	N	N
Thermo-Electric	N	N	P-S	N	N	N	N	N	G-P	N	N	N	N
X-ray Fluo-rescent Spectrometer	N	N	N	N	N	N	N	N	G	G	N	N	N

* - Magnetic Materials Only
G - Good
P- Poor
N- Not Applicable
S- Surface Only

TABLE 2-4. Typical Quality Characteristics Appraisable By Non-Destructive Tests

SOUNDNESS

- Flaws at or within 1/8 in.

  Cracks
  Inclusions, metallic of non-metallic
  Porosity
  Undercuts
  Inadequate penetration
  Incomplete fusion
  Laminations or lack of bond
  Burn-through or drop-through
  Slugging

- Subsurface Flaws

  Cracks
  Inclusions
  Porosity
  Inadequate penetration
  Incomplete fusion
  Laminations or lack of fusion

MECHANICAL PROPERTIES

- Hardness
- Miscellaneous structure-sensitive properties, and sorting

CHEMICAL PROPERTIES

- Carbon Content
- Macro analysis and sorting
- Micro analysis

DIMENSIONS

- Thickness
- Location or position of hidden components
- Location and size of flaws

SURFACE ROUGHNESS

METALLURGICAL STRUCTURE

CHAPTER 3

CURRENT WELD DEFECT ACCEPTANCE STANDARDS

3.1 General

As noted earlier, designers have come to rely on weld defect acceptance limits, established in various inspection codes, to ensure the integrity of a welded structure. One might ask what comprises an ideal weld defect acceptance standard. For a standard to be considered ideal, it would have to have a wide variety of attributes. These might include applicability to all types of steels having any combination of surface condition, heat treatment, coating, etc.; applicability under any stress, temperature, or environmental conditions; and usefulness for any type, shape and size of weld defect. An ideal standard would also account for particular characteristics of the structure, the possibility of the existance of residual stresses and of stress concentrations. For a single acceptance standard to meet such requirements is indeed a tall order, even if one resorts to the use of a computer.

The role that the welding process takes in degrading the initial properties of materials, as well as the importance of residual stresses and weld defects, are still being investigated, and all the answers are still not available or understood. It is the complex interplay of these factors which prevents the establishment of simple rules which would be applicable to a wide range of problems.

Acceptance standards today are usually drafted emperically, and fall far short of possessing wide applicability. Weck[29] has gone as far as to say that some authorities "have produced porosity charts and rules for permissible sizes of other defects which, in the complete absence of any factual or experimental basis, must have been the result of divine inspiration of the code makers".

The introduction of acceptance limits, based on the results of non-destructive examination, dates back many years to the time when little or nothing was known about the role of weld defects in the initiation of fracture. As we have seen, non-destructive testing has proven to be an efficient and revealing method of detecting weld imperfections. One might conclude that NDT is almost too effective, since smaller and smaller defects in welds are being detected. This aggravates the problem of establishing a tolerance level for defectiveness.

With little background upon which to base an evaluation of the significance of weld defects, the code makers selected purely arbitrary methods of establishing defect limits. This represented a stop-gap measure upon which the majority of non-destructive test acceptance levels still rely.[32] Thus, most acceptance levels specified in today's codes and standards merely attempt to define the normal limits for practical welding and are rarely, if ever, based on scientific facts.[32]

3.2 Code Requirements

Greater insight into the nature of current defect acceptance codes and standards can be achieved through a more detailed investigation of a specific acceptance code. For this purpose, the ASME Boiler and Pressure Vessel Code will be used. This code represents one of the oldest, most successful and most widely recognized and accepted documents of its kind.[26]

The first ASME Boiler Code appeared in 1914. A completely chaotic jumble and confusion of rules for boiler construction existed at the time, and the code represented an attempt to bring some semblance of order to the situation. Since then, the code has been frequently modified to keep pace with revolutionary engineering developments in steam generation, pressure containment, size of components, environmental conditions ranging from cryogenic temperatures to some of the very high temperature, high pressure applications of the chemical and petrochemical industries. Most recently it was expanded to take in the nuclear field.[26]

Various requirements and defect acceptance standards for welds and weldments as specified in the ASME Boiler and Pressure Vessel Code[30] will now be discussed.

The ASME code required a visual examination of the weld joint preparations to ensure proper fitting, alignment, positioning, joint dimensions, cleanliness and soundness of surfaces to be joined. The finished weld requires a visual inspection to ensure that the weld has complete joint

penetration, freedom from undercut, no overlay, and no abrupt ridges or valleys. The code also requires that the weld surfaces be reasonably smooth and either flush with the adjoining surfaces, or have a limited amount of weld reinforcement merging smoothly into the base metal surface.

Sample or test welds must pass certain visual, destructive and non-destructive tests. Each weld procedure must be qualified by the preparation of a sample weld for each stated class of base material, weld metal, and thickness range. Samples removed from the test plate are then subjected to specified tests to establish that the procedure is capable of producing sound welded joints, meeting prescribed visual and mechanical requirements.

Although visual examination, pressure and leak testing, and qualification of weld procedures are important code requirements, one normally thinks in terms of non-destructive testing when weld defect acceptance codes and standards are discussed.

ASME codes specify that any section "shown by radiography to have any of the following types of imperfections shall be judged unacceptable and shall be rejected" -- any type of crack or zone of incomplete fusion or penetration; elongated or intermittent aligned slag or inclusions within certain measured limits of length and spacing; and the size, quantity and distribution of porosity as represented in charts provided in the code.

While ultrasonic examination is an important NDT technique, particularly in determining the presence and dimensions of cracks, the present ASME code only requires ultrasonic examination of electro-slag welds, and welds in certain nozzle configurations. In both instances, it is used in addition to, rather than in place of, radiography. The introduction into the code of ultrasonic procedures and acceptance limits is very difficult, since the test procedures must be spelled out in great detail. This is necessary because the operator manipulative and interpretive skills play such an important role in the test procedure.(26)

Magnetic particle and penetrant type testing are used principally in the examination for defects in the plate surfaces, the cut edges of weld joint preparations, and the surfaces of finished weldments. Penetrant and magnetic particle techniques are sometimes considered simply as aids to visual examination.(26)

Most all defect standards relate to each other. ASME, Navy, ABS, British Standard, etc., provide codes that are very similar in content. Table 3-1 gives various acceptance standards established by the more important codes.

3.3 Evaluation of Acceptance Codes and Standards

One of the major difficulties with acceptance codes and standards is that they allow no provision for relating the acceptance limits to service performance. In the case of cracks, for example, one must simply live with the code requirement that all weldments which contain cracks or crack-

TABLE 3-1

CURRENT WELD DEFECT ACCEPTANCE STANDARDS AS FOUND IN VARIOUS CODES

Defect / Code	Cracks and crack-like defects	Weld Surface	Undercut / Overlap	Reinforcement	Porosity	Inclusions
A.S.M.E. Boiler and Pressure Vessel Code	Not Allowed	Reasonably Smooth	Freedom from Undercut No Overlap	Limited Amount	As Determined from Charts	Not allowed if length is $\frac{1}{4}$ in. for T up to $\frac{3}{4}$ in. $(\frac{1}{3})$T for T from $\frac{3}{4}$ in. to $2\frac{1}{4}$ in. $\frac{3}{4}$ in. for T over $2\frac{1}{4}$ in. T = thickness of weld
A.B.S.	Not Allowed	Regular and Uniform	Reasonably Free	Minimum Amount	Reasonably Free	Reasonably Free
NAVY	Not Allowed	No Surface Damage	Reasonably Free	Limited Amount	As Determined From Charts	Not to Exceed Specified Limits

like defects must be rejected - the part discarded or the weld repaired. There is no room for an assessment of the significance of the crack to the overall service performance of the structure.

Because of these considerations, the ASME Boiler and Pressure Vessel Code, as well as similar codes, have received considerable criticism. We must, however, temper this criticism with the realization that existing acceptance standards and codes developed to fulfill an urgent need and, in most cases, have functioned well. The developers of codes have been placed with an enormous task, and the results of their labor are codes and standards which represent a compromise between cost, serviceability, and experience which has evolved over the years on the part of material producers, fabricators, and structural designers. Traditional acceptance levels provide a modest insurance against brittle fracture, if the material is reasonably suitable for service. Due to the requirements for smooth surfaces, they have also proved to be adequate under all but the worst of fatigue conditions.[32]

In the light of all this, one must still appraise the impact that the adherence to traditional acceptance standards implies. In notch ductile mild steel, for example, the application of current acceptance standards will require the repair of welds due to the presence of inconsequential weld defects. The result of this is, of course, the danger of weakening the weld due to the repair welding and additional costs. Masubuchi et.al.,[7] are convinced that well over 50%

of all repair welds performed today are unnecessary. With the current improvements in the detection capabilities of non-destructive test techniques, this trend will no doubt continue, with ever increasing numbers of welds rejected. Without a more rational approach to the assessment of the significance of weld defects, there is little that can be done to combat this worsening situation.

Considerations such as these are of even greater importance in this economic climate of increasing costs. It is a sad fact of life that repair welding is very costly. The high cost is made even worse, when one considers that it is not uncommon for weld repairs to be made several times, at the same location, before a satisfactory repair is achieved.

Major areas of product cost most seriously affected by the current lack of realistic weld defect acceptance standards include:[13]

1. Fit-up - man hours expended to set up parts in elaborate weld tooling, when preparing for welding.

   Machining - costs incurred in accurately machining and sizing parts to meet small allowances for mismatch and gap.

2. Tooling - highly restrictive level of acceptance for mismatch, undercut, porosity and inclusions require excessive design and fabrication costs for elaborate tooling.

3. Inspection - complex and expensive inspection methods are required for most weldments. The inspected weld may require the removal of small defects, without regard to the impact of the defect on the serviceability of the structure during its expected lifetime.

4. Rework - reinspection after rework is necessary, and often a second and third rework will be required before the acceptance standard can be satisfactorily met. This added expense is even harder to justify when the rework itself may reduce joint strength more than the original imperfection. In some metals, rework may reduce the joint strength to a degree that the efforts and expense incurred in developing new welding techniques to produce higher strength welds are all but negated.

Figure 3-1[13] shows the percent of cost increase for these four major elements. These percentages are clearly not insignificant!

Fabricators, who can no longer live with these high and rising costs and the other limitations of the traditional acceptance standards, must agree that a new approach to weld defect acceptance standards is needed. Obviously, this new approach should be based upon the assessment of the significance of the weld defect on the service of the structure during its expected lifetime. Under a revised code, flaws that would

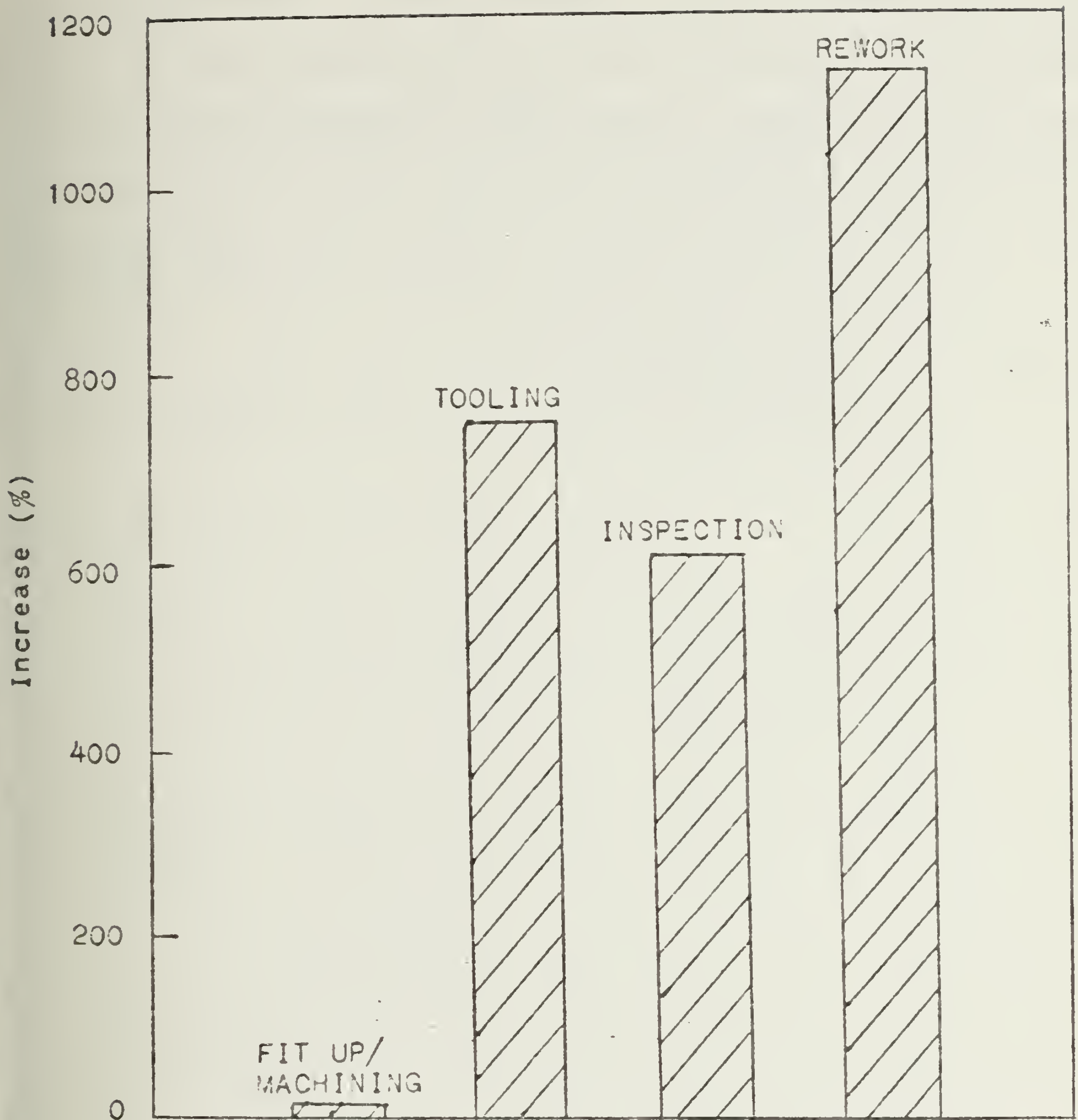


FIGURE 3-1. Weld Cost Increase

not lead to premature failure could remain in the weld. It is proposed that the application of fracture mechanics concepts to the problem of weld defect assessment would provide a more rational basis for weld defect acceptance standards. The remainder of this paper will be devoted to developing fracture mechanics concepts and applications.

CHAPTER 4

WELD DEFECT ASSESSMENT CONCEPTS

4.1 Linear Elastic Fracture Mechanics Theory

The literature on fracture mechanics is voluminous, and it is not the intent of this paper to repeat complex technical details. Nevertheless, the appreciation of certain fundamentals is essential, prior to the application of fracture mechanics to the assessment of weld defects.

Linear elastic fracture mechanics is the basic theory of brittle fracture. In 1920, Griffith developed a criterion for brittle fracture for ideal brittle materials, based on an energy balance between the elastic energy and the surface energy.[67] This energy balance indicated whether the extension of a crack would be stable or unstable. More recently the emphasis has been on local stress and strain conditions at the crack tip, in the belief that crack growth will occur when certain critical conditions exist at the crack tip.[69] Criteria are established for fracture instability in the presence of a crack, based on stress intensity considerations. The object of the theory is to relate the stress field developed in the vicinity of a pre-existing crack tip, to the applied nominal stress on the structure, the material properties and the size of defect necessary to cause failure.

The elastic stress field in the vicinity of a crack tip can be characterized by a parameter designated the stress intensity factor K_1. The subscript "1" is often used to

designate the opening mode of crack surface displacement. In the opening mode, the tension stresses are perpendicular to the major plane of the flaw. The magnitude of the stress intensity factor is dependent upon the geometry of the body containing the crack, the size and location of the crack, and the distribution and magnitude of the external loads on the structure.[66,35] The relationship between these parameters can be written in the following general form:

$$K_1 = M\sigma \left(\frac{\pi a}{Q}\right)^{1/2} \tag{4.1}$$

where K_1 = the stress intensity factor

σ = the gross stress

a = the crack length

M = a constant which is dependent on various configurational considerations

Q = a constant which is dependent on flaw shape

Several expressions for specific relationships between K_1 and various flaw shapes and external loads are given in Appendix A.

In the presence of a crack or crack-like defect, failure will occur whenever the stress intensity factor, K_1, reaches or exceeds some critical value of stress intensity designated K_{1c}. This establishes the criterion for brittle fracture in the presence of a crack. For the opening mode of loading under plane strain conditions, i.e., limited crack tip plasticity, the critical stress intensity factor is

considered a material property. This material characteristic represents the material's inherent resistance to failure when a crack or crack-like defect exists in the structure. It is frequently referred to as the fracture toughness of a material.

Pellini[35] has indicated that $(K_{1c}/\sigma_{ys})^2$ properly defines fracture toughness and not K_{1c} alone. Here, σ_{ys} is the yield strength for static loading. It has been substantiated that unstable crack movement depends on the formation of a critical plastic zone size, and that the larger the plastic zone size at fracture, the tougher the material.[35] Pellini has shown that the critical plastic zone size is, in fact, a function of $(K_{1c}/\sigma_{ys})^2$. A low ratio of $(K_{1c}/\sigma_{ys})^2$ means a small plastic zone size, indicating little energy expenditure in developing the unstable crack. Such a material is considered brittle. Therefore, a value of K_{1c} cannot be translated into fracture toughness unless the yield stress is specified. For a given value of K_{1c}, a low yield stress will cause the $(K_{1c}/\sigma_{ys})^2$ ratio to be large. This indicates a high plane strain fracture toughness, because of the large critical plastic zone size. If, on the other hand, the yield stress is high, the ratio will be small, denoting low toughness due to the small critical plastic zone size.

Figure 4-1[35] provides a graphic illustration of a sharp crack with a small plastic zone and the associated elastic stress field. The intensity of the stress field, which is represented by the steep rise in the stress on

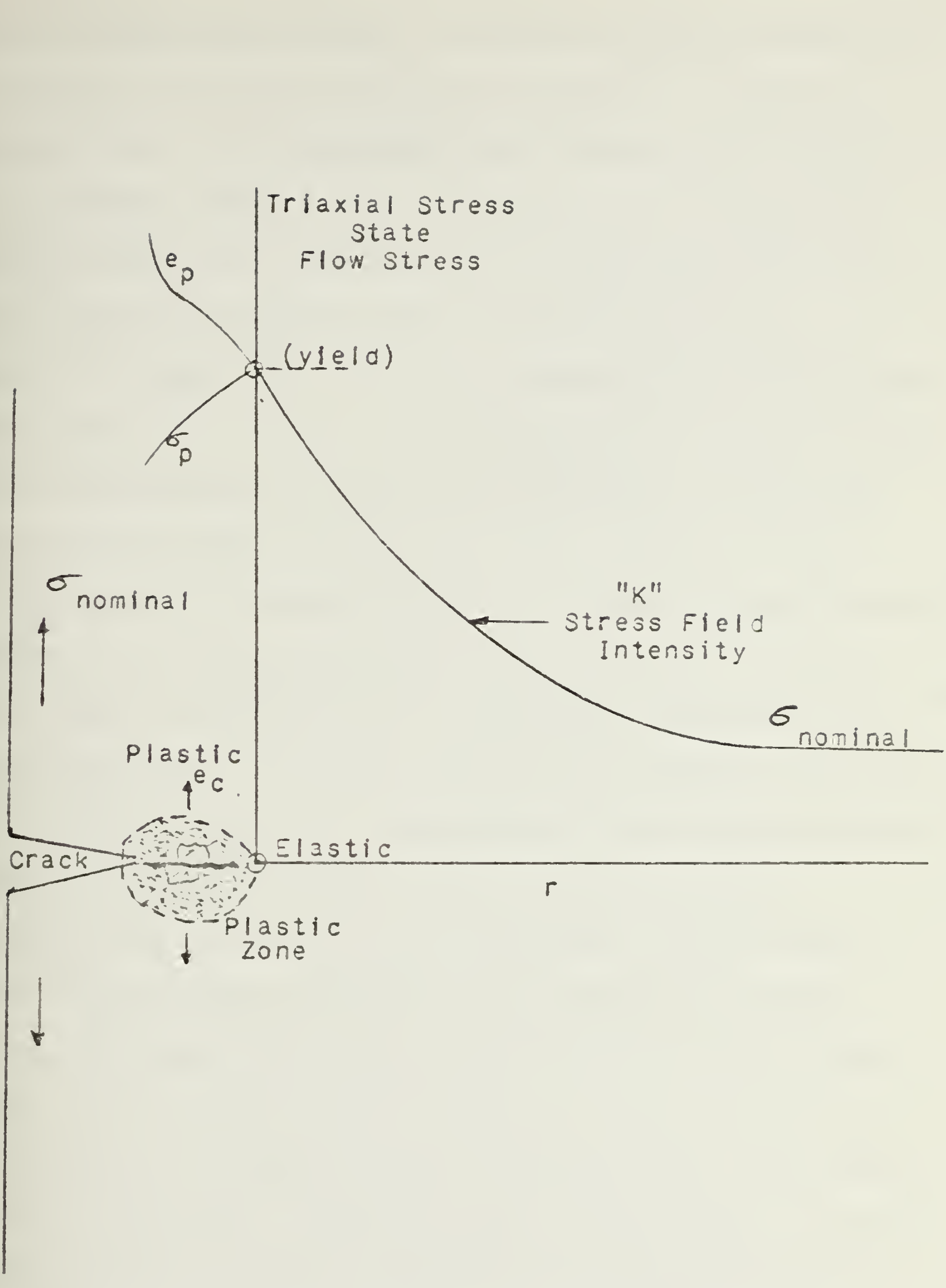


FIGURE 4-1. Relationships of elastic and plastic stress fields to the plastic zone at crack tips for the case of plane strain constraint.

approach to the plastic zone, is defined by the parameter K_1.

While K_{1c} is a basic material parameter, it must be recognized that it is dependent upon mechanical and metallurgical variables. Strain rate and temperature are the most significant mechanical variables. For materials which have a strong temperature and strain rate sensitivity, K_{1c} generally decreases with decreasing temperature and increased loading rates.[66] Caution should therefore be taken to use K_{1c} date obtained under loading and temperature conditions corresponding to those prevailing in the actual structure. In a like manner, consideration must be given to metallurgical variables such as heat treatment, microstructure, rolling texture, steel making practice, impurities, inclusions, etc.[66] As with temperature and strain rate, it is essential that test material used in making K_{1c} measurements have characteristics similar to the material used in the actual structure.

Where welded structures are concerned, one must also consider the fracture toughness of all components of the weldment, the base metal, heat affected zone and weld metal deposit.

In addition to those factors discussed above, the thickness of the plate has an effect on the value of K_{1c}. It has been shown that the fracture toughness of a material will decrease with increasing plate thickness.[37,65]

4.1.1 Failure Criterion

The criterion for brittle failure in the presence of a crack has been stated to be when K_1 reaches or exceeds K_{1c}. From the general relationship for K_1 given in equation (4.1), an expression for the critical flaw size to cause brittle failure can be determined. Thus

$$a_{cr} = Q/\pi \ (K_{1c}/M\sigma)^2 \tag{4.2}$$

If the design stress is a given ratio of the yield stress, the maximum allowable defect size can be expressed by the relationship:

$$a_{cr} = \text{Constant}(K_{1c}/\sigma_y)^2 \tag{4.3}$$

4.1.2 Limitations

Accepted use of linear elastic fracture mechanics is confined to the plane strain condition. Plane strain is defined as a state of stress which results in a zero strain along a specific direction.[67] For plane strain conditions to be dominant, the relationship

$$B \geq 2.5(K_{1c}/\sigma_{ys})^2 \tag{4.4}$$

must be satisfied.[69,40,35] In equation (4.4), B is the material thickness, K_{1c} is the critical stress intensity factor, and σ_{ys} is the yield strength for static loading.

The limitation to plane strain conditions means there is a maximum fracture toughness level which can be measured for a given thickness of a particular material. This level is given by:

$$K_{1c} \leq \sigma_{ys} \sqrt{.4B} \qquad (4.5)$$

As an example, for 2 inch thick steel with a yield stress of 40 KSI, the maximum plane strain toughness which could be measured is about 36 KSI $\sqrt{\text{IN.}}$ However, for 6 inch thick low alloy steel with a yield of 65 KSI, the maximum plane strain toughness that could be accurately measured is about 100 KSI$\sqrt{\text{IN.}}$

For all practical purposes, a value of $K_{1c}/\sigma_{ys} = 2$ represents the limit of plane strain fracture toughness.[35] If the section size of the material under consideration must be made so large as to be inpractical, in order to meet plane strain conditions, then K_{1c} simply cannot be obtained.

By limiting the use of linear elastic fracture mechanics to the plane strain regime, it is assured that the fracture will occur under small scale yielding conditions (yield zone size at the crack tip is small compared with the crack size).

Plain strain conditions generally limit the application of linear elastic fracture mechanics to relatively brittle, high strength materials, or to the lower strength materials, if used in thicknesses that provide essentially plane strain conditions of loading.

4.1.3 Stresses

Before going on to discuss other aspects of linear elastic fracture mechanics theory, a few words should be said concerning stresses. A knowledge of stresses represents the third requirement for fracture mechanics analysis, the other two being knowledge of the material properties, and defect characterization.

The necessary stress information can be obtained by any method of conventional stress analysis which defines the applied nominal stresses acting on the structure. In conducting such an analysis, the presence of the defect is ignored for cases where the defect is small in comparison to the size of the component.

As in any stress analysis, the effects of thermal and residual stresses must be appropriately included. During the welding process, residual stresses of yield point value may develop. When the residual stresses are superimposed on the applied (design) loading, the stress intensity factor will be greater than without residual stresses. This effect is shown graphically in Figure 4-2.[65]

4.1.4 Linear Elastic Fracture Mechanics Applied to Fatigue

Fatigue failure represents one of the most common types of failures in welded structures. This is brought about by the fact that most weld joints have poor fatigue properties. Since fatigue is a fracture mechanism critically affected by weld defects, the inevitable existance of defects in

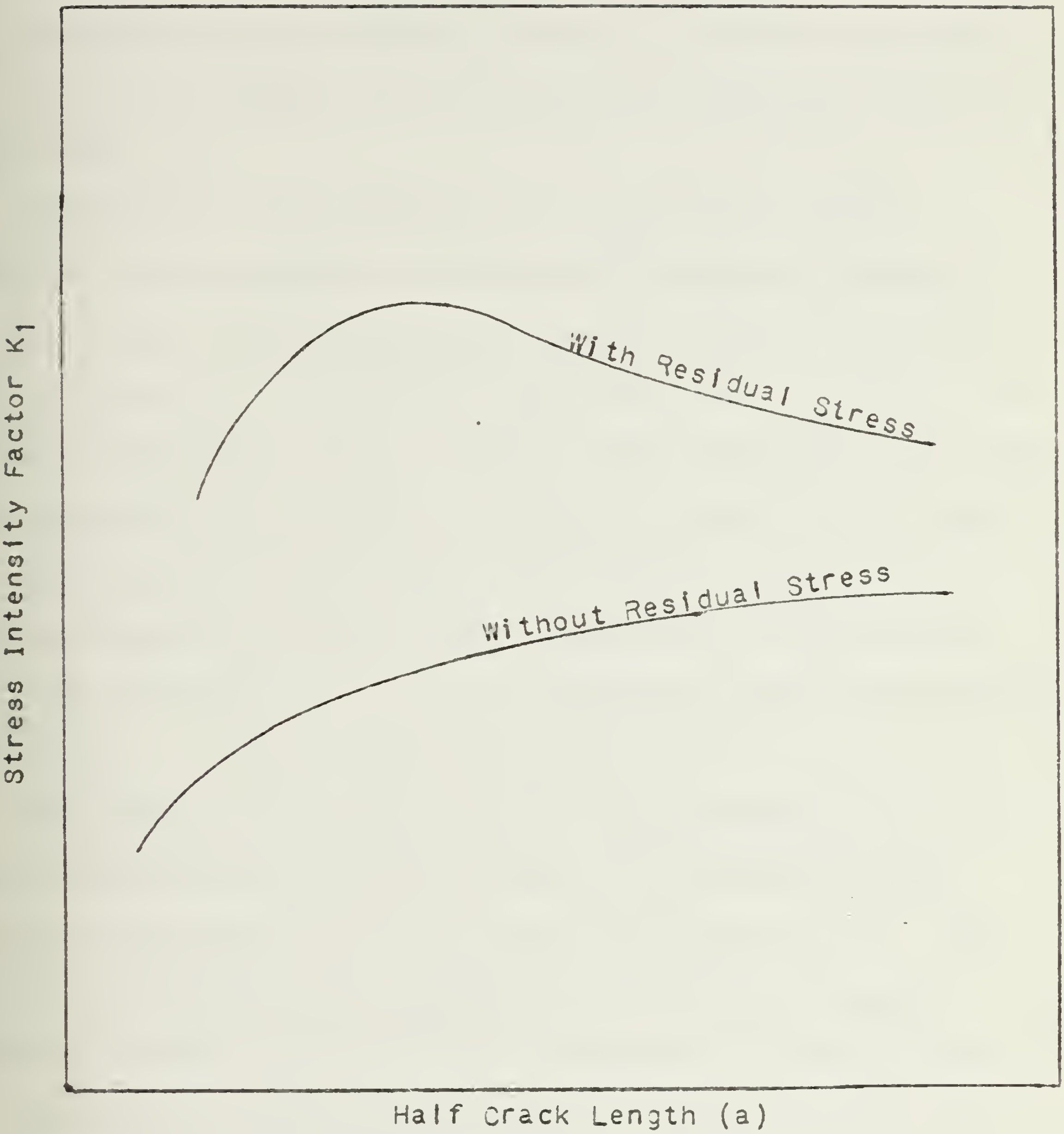


FIGURE 4-2. Effect of residual stress on K_1 - a curve.

welded joints makes the problem of fatigue particularly accute. Figure 4-3[8] shows the effect of defects on the fatigue strength of butt welds in low carbon steel. It is well known that from a fatigue strength viewpoint, defects on or near the surface are more damaging than those imbedded in the weld.[8,6]

To determine the influence of fatigue on a welded structure, it is necessary to establish reliable methods of assessing the significance of flaws under fatigue conditions. Fatigue analysis is especially important under a "fitness for purpose" design philosophy, whereby flaws which will not bring about premature failure may be allowed to remain in the weld.

Ideally, methods should be developed to determine the fatigue strength of welded joints containing a pre-existing crack or flaw subject to any load history and for any failure criterion.

The most promising approach to this problem lies in the use of linear elastic fracture mechanics technology based upon the description of fatigue crack propagation.[53] The analysis of fatigue crack growth rate in terms of stress intensity factors has gained wide acceptance in recent years.[54]

In a welded joint, the existance of severe stress concentrations and a weld defect, can lead to the initiation of fatigue cracks very early in the life of the structure. The total useful life under cyclic loading conditions is therefore dependent upon the rate of growth of the flaw from a subcritical size, to a critical size. For given conditions

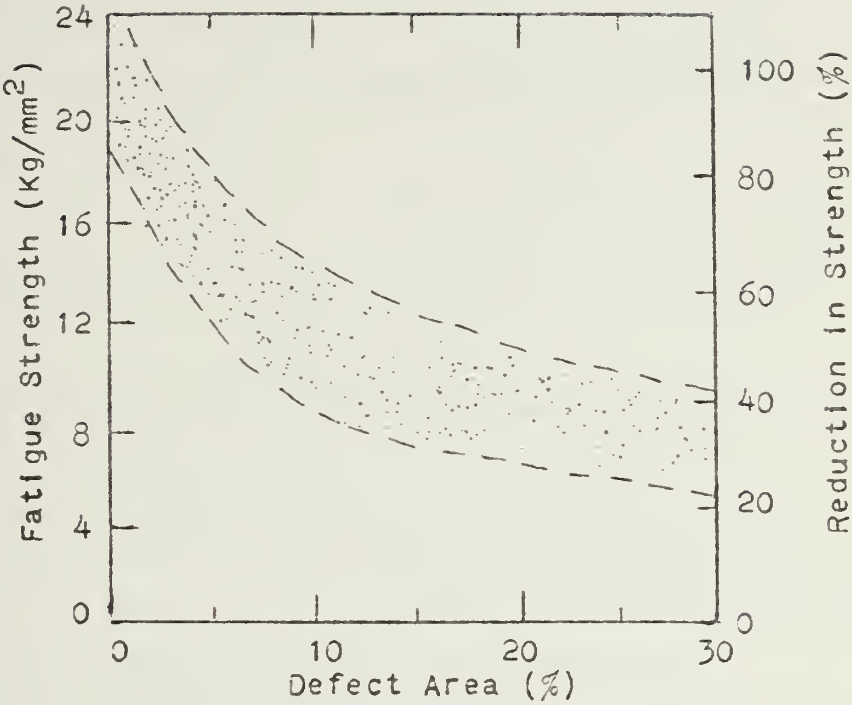


FIGURE 4-3. Reduction in fatigue strength due to defects in mild-steel weldments.

of geometry (flaw and component), material, temperature and environment, the crack growth rate can be shown to be dependent upon the stress intensity range being applied during cyclic loading.[66,52,53]

There is much information in the literature concerning fatigue crack growth laws. All such laws can be reduced to a single simple expression:

$$da/dN = C(\Delta K)^{m} \tag{4.6}$$

where m = the slope of the log da/dN versus logΔK relationship

C = an emperical constant dependent upon material properties, frequency, mean load, and other secondary variables

ΔK = the range of stress intensity factor being applied during each cycle of loading

da/dN = the change in crack length during each cycle

Since a given value of stress intensity factor is proportional to the stress at the tip of any crack, and provided factors not related to ΔK, such as material or environment, remain constant, the relationship between da/dN and ΔK may be regarded as a law of crack propagation relevant to any geometry of cracked structure.[53]

Although many attempts have been made to deduce a law of fatigue crack propagation theoretically, none have been found

that fully agree with observed crack propagation behavior. Because of this, crack propagation relationships are deduced from test data.

Even though the relationship between ΔK and loading takes into account corrections for geometry, it is found, in practice, that da/dN versus ΔK data can be affected by geometry. The various regions which can develop in the data due to geometry are shown in Figure 4-4.[53] As is seen from the figure, only Region 2 is of interest in the context of fatigue cracks associated with welded joints, since it obeys equation (4.6). This is the only region which achieves a predominantly plane strain fracture mode.[53]

For the constants "C" and "m" of equation (4.6), Kitagawa and Misumi[56] have established the relationship:

$$C = A/B^m \tag{4.7}$$

where 'B' is about 55 for various metals and 'A' is about $.5\times10^{-4}$ for ΔK given in $\text{KG-MM}^{-3/2}$ and da/dN in MM(Cycle)^{-1}. This relationship is shown in Figure 4-5.[56] Equation (4.7) has been shown to be applicable to a wide range of structural steels and fairly good for all b.c.c. metals. For f.c.c. metals, including austenitic steels, the same relation can be used, but in this case, 'A' should be larger than $.5\times10^{-4}$ where 'B' is 55 as shown in Figure 4-6.[56]

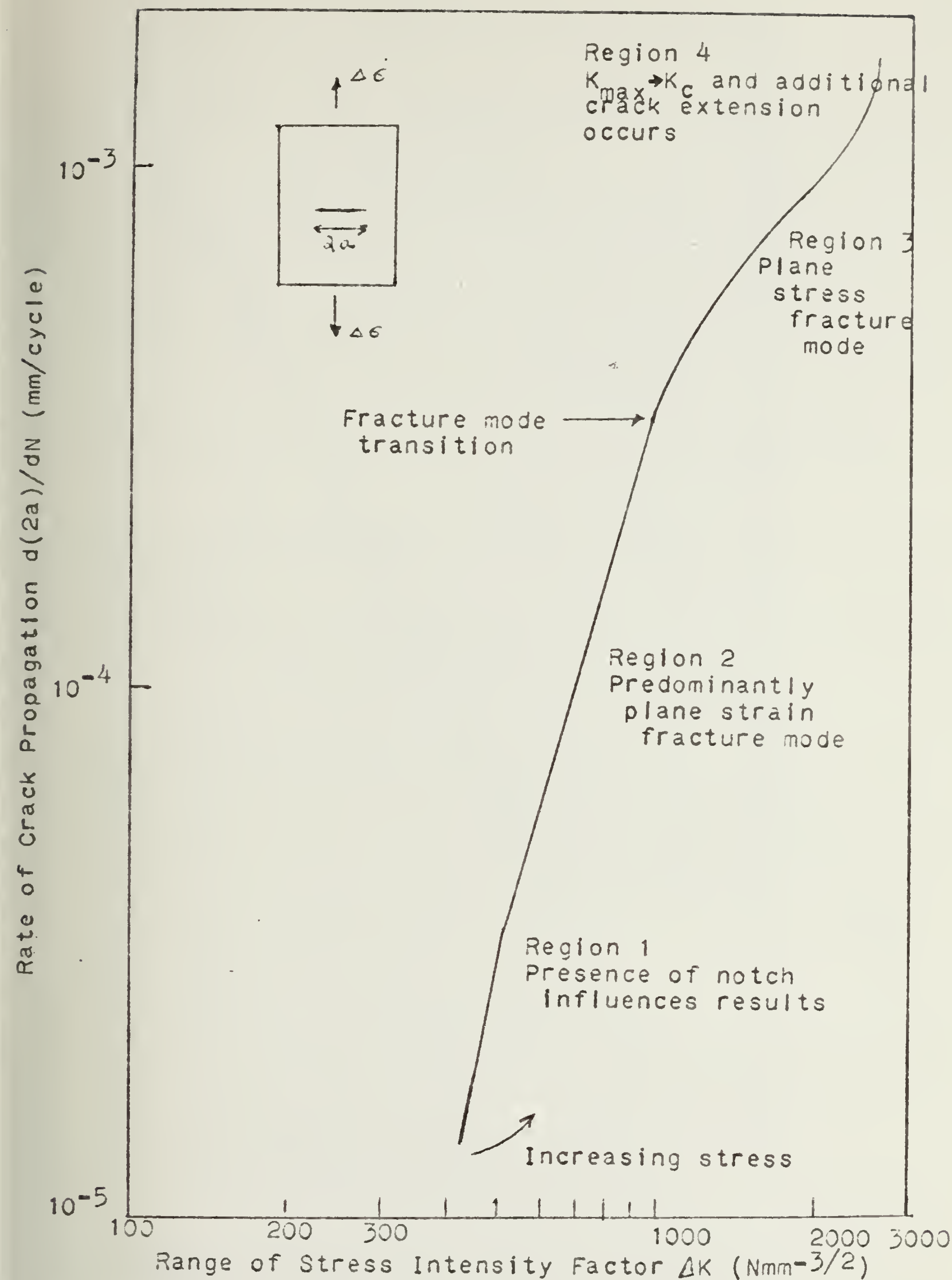


FIGURE 4-4. Relation between crack propagation curve and fracture characteristics for a center-cracked plate.

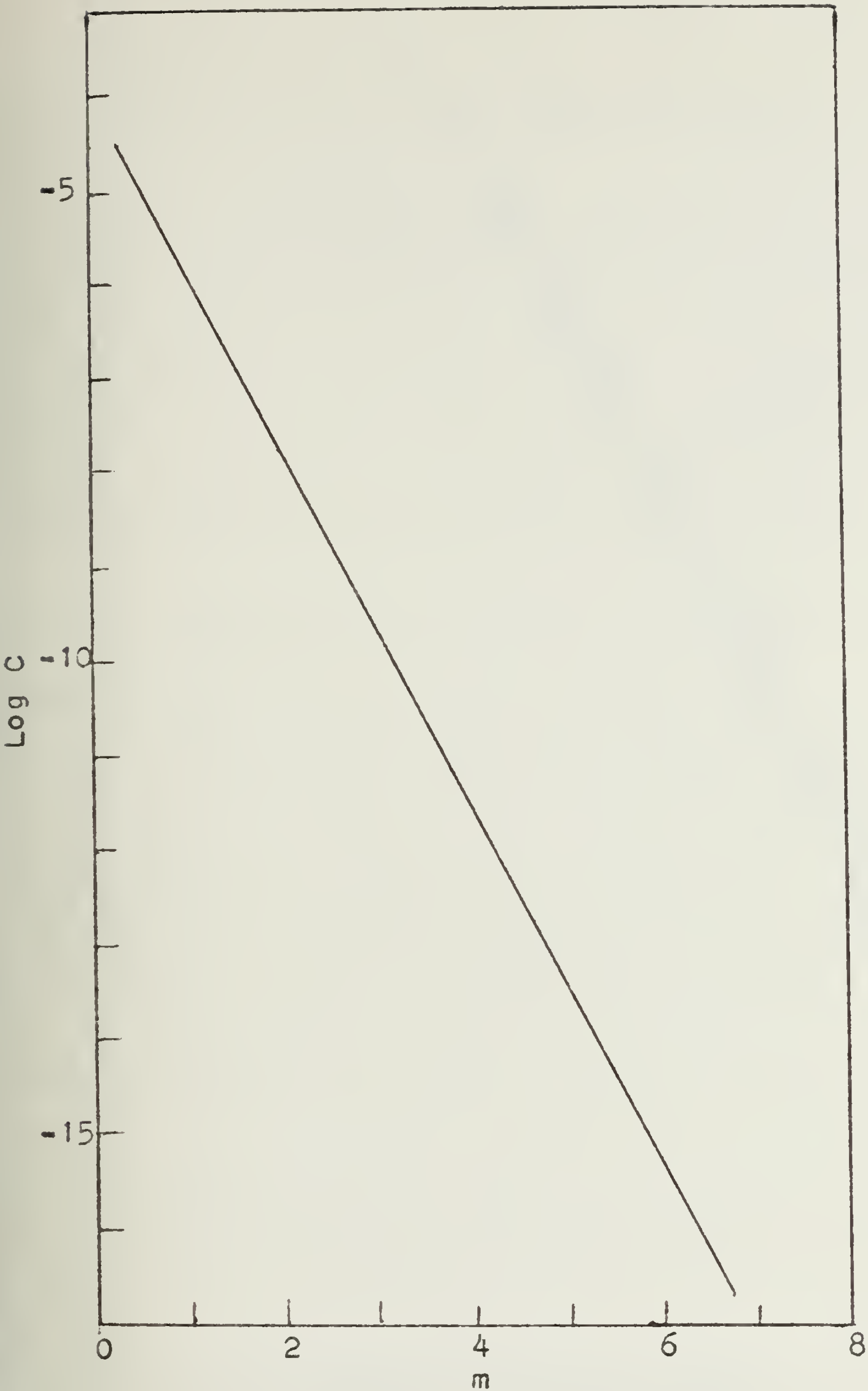


FIGURE 4-5. Relation between C and m for $da/dN = C\,(\Delta K)^m$.

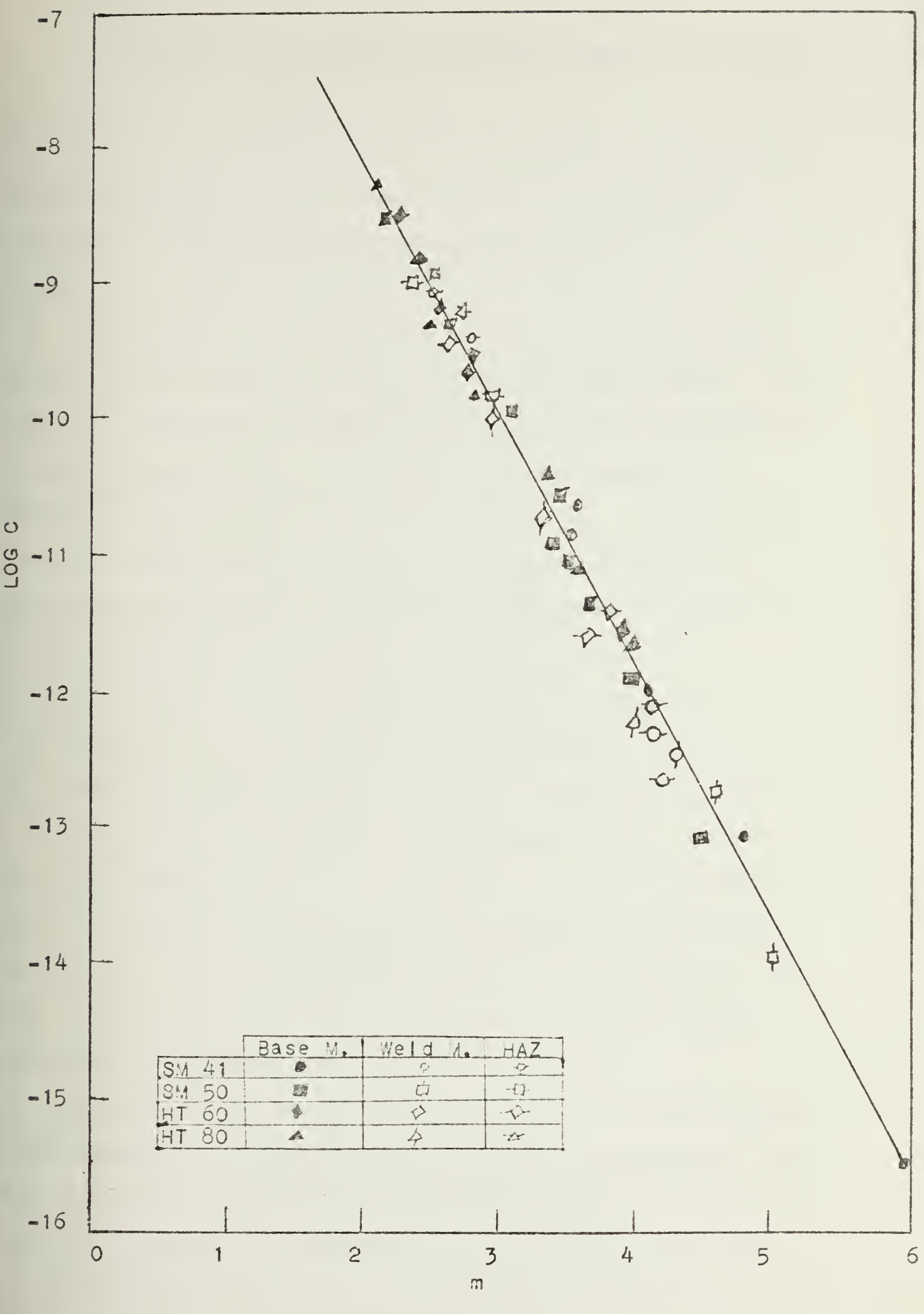


FIGURE 4-6. C - m relation for structural steels.

4.1.4.1. Factors Affecting the Crack Propagation Law

Although equation (4.6) has wide practical application, it must be recognized that many factors can affect both the constants in the equation and the actual form of the relationship.

It is obvious that the rate of fatigue crack propagation depends on the material through which the crack passes. However, for a specific material, the rate of crack propagation is almost insensitive to changes in microstructure and mechanical properties, unless they give rise to changes in fracture characteristics.[52] This change in fracture characteristic results, for example, when a static mode of fracture accompanies the normal fatigue process.

For welded joints in structural steels, the general insensitivity of crack propagation to changes in microstructure and mechanical properties is shown in Figure 4-7.[53]

From experimental results like those given in Figure 4-7, it can be concluded that the same law of fatigue crack propagation will govern the progress of a fatigue crack through the various regions associated with a weld (weld metal, HAZ, base plate), provided that a static fracture mode does not accompany the fatigue process.[52,54]

Only one factor has been found, associated with welding, which affects the rate of crack growth in a significant way. This factor is the residual stress state which arises as the result of constraints developed on cooling.[54] From the

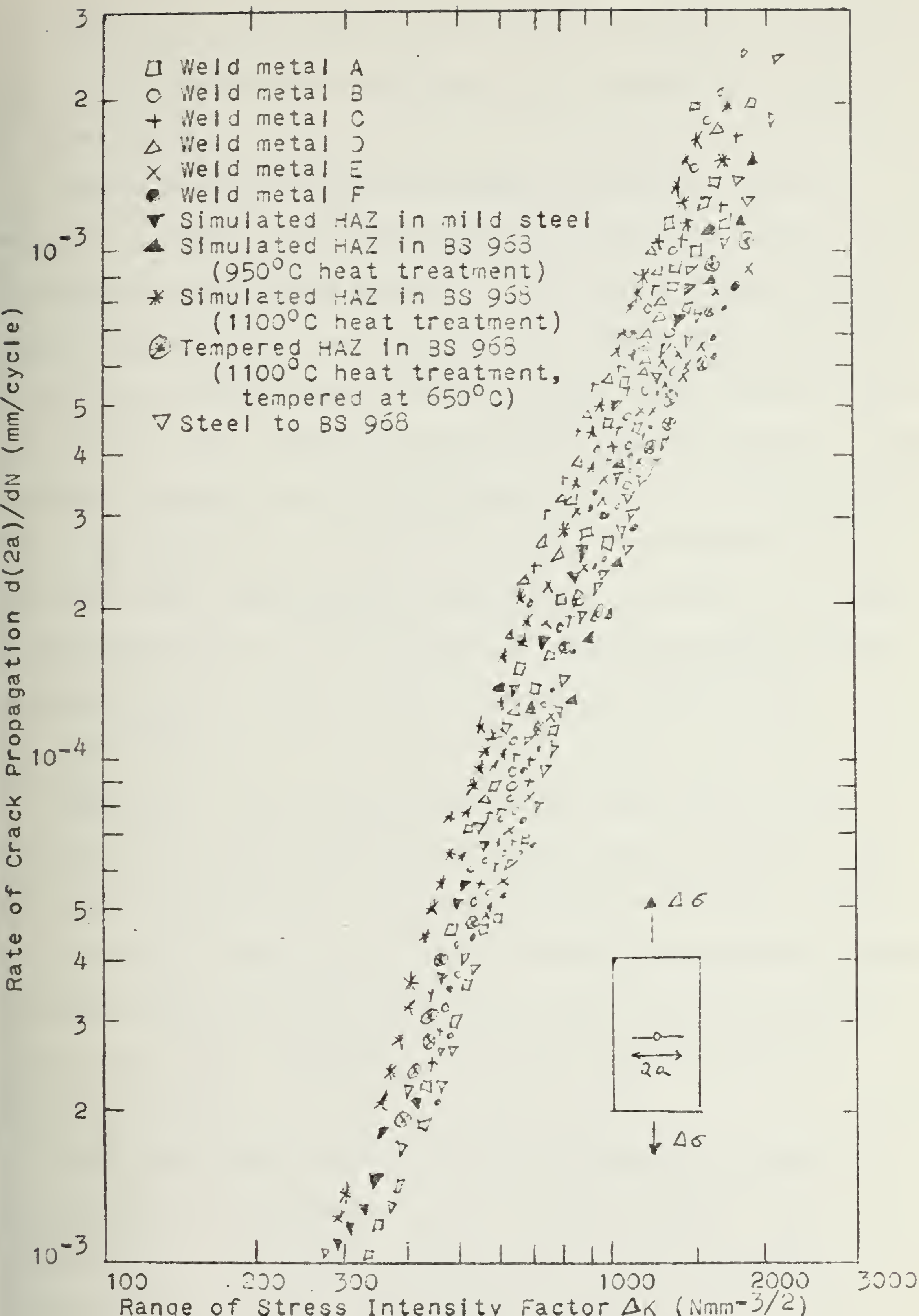


FIGURE 4-7. Fatigue crack propagation data for structural C/Mn steel weld metals, HAZs and parent plate.

viewpoint of fatigue crack growth, these residual stresses appear to be beneficial, and have led to marked reduction in growth rates.

For structures in the as-welded consition, residual stresses are often of yield stress magnitude and acting in a direction of subsequent loading. The result is that fatigue cracks propagate in regions where the total stress consists of a static maximum stress equal to yield (the residual welding stress), and a cyclic stress range (applied stress). The residual stresses are thus superimposed on the applied stress cycle, resulting in an effective stress consisting of the applied stress range cycling downwards from yield. For such welded structures, it is relevant to consider fatigue crack propagation only under conditions of high tensile mean stresses.[(53)]

McEvily[(54)] has referenced studies which show 1) no difference in crack growth rate either with or against the direction of welding; 2) a characteristic of fatigue cracks to slow down as they approach the residual compressive stress field of a weld; and 3) that cracks never follow the weld-parent metal HAZ interface, but always deviate into the softer material.

One final factor which can have an extreme effect on fatigue crack propagation is that of environment. The fatigue life of a welded structure can be significantly reduced by the action of an agressive environment. This fact must be kept in mind when a crack propagation law based

on test data is applied in practice, since the law may only be applicable to fatigue in air at room temperature.

Before going on to describe the analysis of the fatigue behavior of a welded structure employing linear elastic fracture mechanics concepts, it is of interest to look at a representative fatigue crack growth rate. Figure 4-8[66] shows the growth rate characteristics of A533, Grade B, Class I steel plate, weld metal and HAZ. The change in slope at ΔK levels below about 25 KSI$\sqrt{\text{IN}}$ suggests that there may be a threshold level of ΔK below which cracks will not grow at any measurable rate.

4.1.4.2 Fatigue Analysis

For the case of constant stress range loading, the analysis of the fatigue behavior of welded joints requires two basic equations. The first is the crack propagation law, assumed to be that given in equation (4.6). The constants "C" and "m" are determined from crack propagation tests of the relevant material. The second relationship is the equation for the stress intensity factor of the crack of interest. For illustrative purposes this will be taken as:

$$K_1 = \sigma\sqrt{\alpha\pi a} \qquad (4.8)$$

where σ = the applied stress

α = a factor related to the component and defect geometry

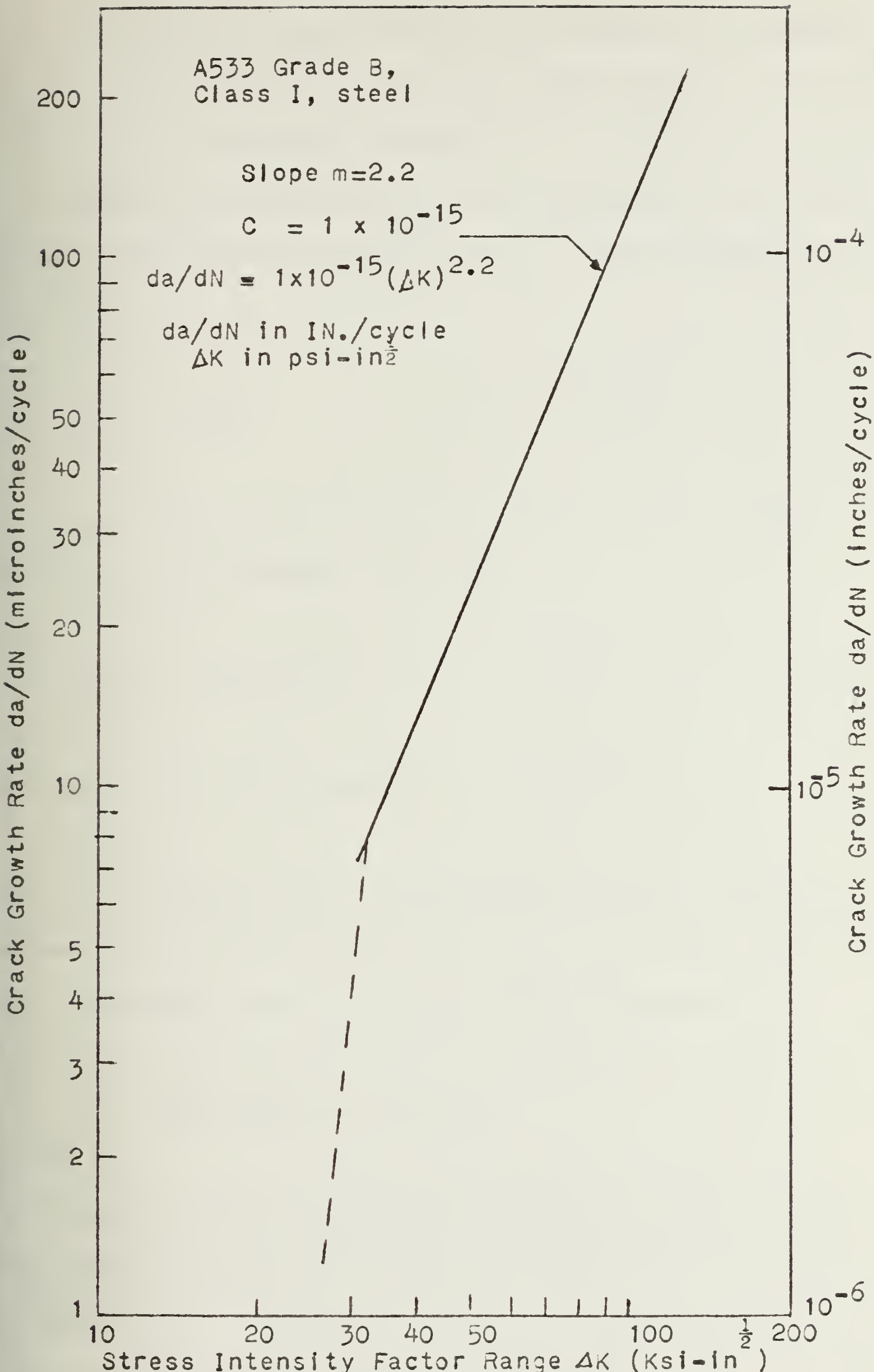


FIGURE 4-8. Summary of crack growth rates for A533, Grade B, Class I plate, weld and heat affected zone.

a = the crack length (total length of an edge of surface crack or half the length of a central or buried crack)

Thus ΔK_1 is proportional to $\Delta\sigma\sqrt{\pi a}$ where $\Delta\sigma$ is the nominal stress range remote from the crack. From equation (4.8), we have:

$$\Delta K_1 = \Delta\sigma\sqrt{\alpha\pi a} \tag{4.9}$$

Following a development by Maddox,[52] equations (4.6) and (4.9) are combined to obtain:

$$da/dN = C(\Delta\sigma\sqrt{\alpha\pi a})^m \tag{4.10}$$

or $$da/dN = C(\Delta\sigma)^m \; (\sqrt{\alpha\pi a})^m \tag{4.11}$$

This is a differential equation which can be integrated between the initial crack size (a_{inl}) and final crack size (a_{cr}) to obtain the fatigue life of a structure.

$$\int_{a_{inl}}^{a_{cr}} da/(\sqrt{\alpha\pi a})^m = C(\Delta\sigma)^m N \tag{4.12}$$

With α, 'm' and 'C' known, equation (4.12) can be utilized to calculate the fatigue behavior N, the endurance to failure, of a defective weld with known initial crack size (a_{inl}), which fails at a known crack size (a_{cr}). In the actual structure, the value of a_{cr} might be taken to be the

critical crack size for brittle fracture, or it may be taken as the material thickness in the case of a pressure vessel where leakage would indicate failure.[8]

The discussion above dealt with the case of constant stress range loading. In reality, most structures experience a variable stress with time. Since there is no limitation to the number of cycles over which equation (4.12) applies, it should be possible to relate fatigue behavior resulting from a sequence of stress ranges of varying magnitude, utilizing equation (4.12) for each block of cycles of a given stress level.

Again, following a development by Maddox[52], consider a sequence of stress ranges $\Delta\sigma_i$ $(i = 1,2,3,\cdots)$ each applied for n_i cycles. The fatigue behavior of a cracked structure under such loading is given by:

$$\Sigma \int_{a_i}^{a_j} da/(\sqrt{\alpha\pi a})^m = C\Sigma(\Delta\sigma_i)^m n_i \tag{4.13}$$

The total fatigue life of a structure with an existing initial crack size, a_{inl}, would be described if the left hand side of equation (4.13) summed to the critical crack size, a_{cr}.

Hence:

$$\sum_{a_{inl}}^{a_{cr}} \int_{a_i}^{a_j} da/(\sqrt{\alpha\pi a})^m = C\Sigma(\Delta\sigma_i)^m n_i \tag{4.14}$$

Considering the constant stress range behavior of the same cracked structure subjected to each of the stress

ranges $\Delta\sigma_i$, we have:

$$\int_{a_{inl}}^{a_{cr}} da/(\sqrt{\alpha\pi a})^m = C(\Delta\sigma_i)^m N_i \qquad (4.15)$$

where N_i refers to the constant stress range endurances.

If a_{inl} and a_{cr} are constant for a particular weld detail, the factor α is also constant which means that the integral of equation (4.15) is a constant.

$$C(\Delta\sigma_i)^m N_i = \text{Constant} = D \qquad (4.16)$$

Now substituting for $\Delta\sigma_i$ in equation (4.14) for failure under variable stress range loading, the expression for $\Delta\sigma_i$ obtained from equation (4.16):

$$\sum_{a_{inl}}^{a_{cr}} \int_{a_i}^{a_j} da/(\sqrt{\alpha\pi a})^m = C \sum \frac{D}{CN_i} n_i \qquad (4.17)$$

But

$$\sum_{a_{inl}}^{a_{cr}} \int_{a_i}^{a_j} da/(\sqrt{\alpha\pi a})^m = \int_{a_{inl}}^{a_{cr}} da/(\sqrt{\alpha\pi a})^m = D \qquad (4.18)$$

From equation (4.17):

$$D = C \sum \frac{D}{CN_i} n_i \qquad (4.19)$$

Therefore for failure:

$$\sum n_i/N_i = 1 \qquad (4.20)$$

Maddox points out that a major inaccuracy in the analysis results from the problem of stress interaction. This inaccuracy is introduced when the affect of a particular stress cycle is influenced by the previous stress history. An example of the effect of a high stress preceding a sequence of lower applied stresses is shown in Figure 4-9.[52] Maddox has even noted cases where a high stress caused a crack to stop propagating altogether.

Before leaving the present discussion of fatigue, a comment on a fatigue analysis approach based upon statistical considerations should be made.

Yurioka[6] proposed that due to the many factors which influence the fatigue life of a structure, it is almost impossible to definitively determine fatigue life. He therefore based an analysis of fatigue life on a statistical approach using a Weibull distribution as the general expression for a distributed function of fatigue failure. The use of a probabilistically distributed fatigue life necessitated the introduction of a concept called utility. Yurioka described utility as the value in use of a set of goods in terms of their quantity or of their attributes. It is a concept which allows comparisons between alternatives based on the quantity or attributes of the alternatives. He goes on to describe how to establish acceptable crack sizes based upon the calculation of the utility of the structure under consideration.

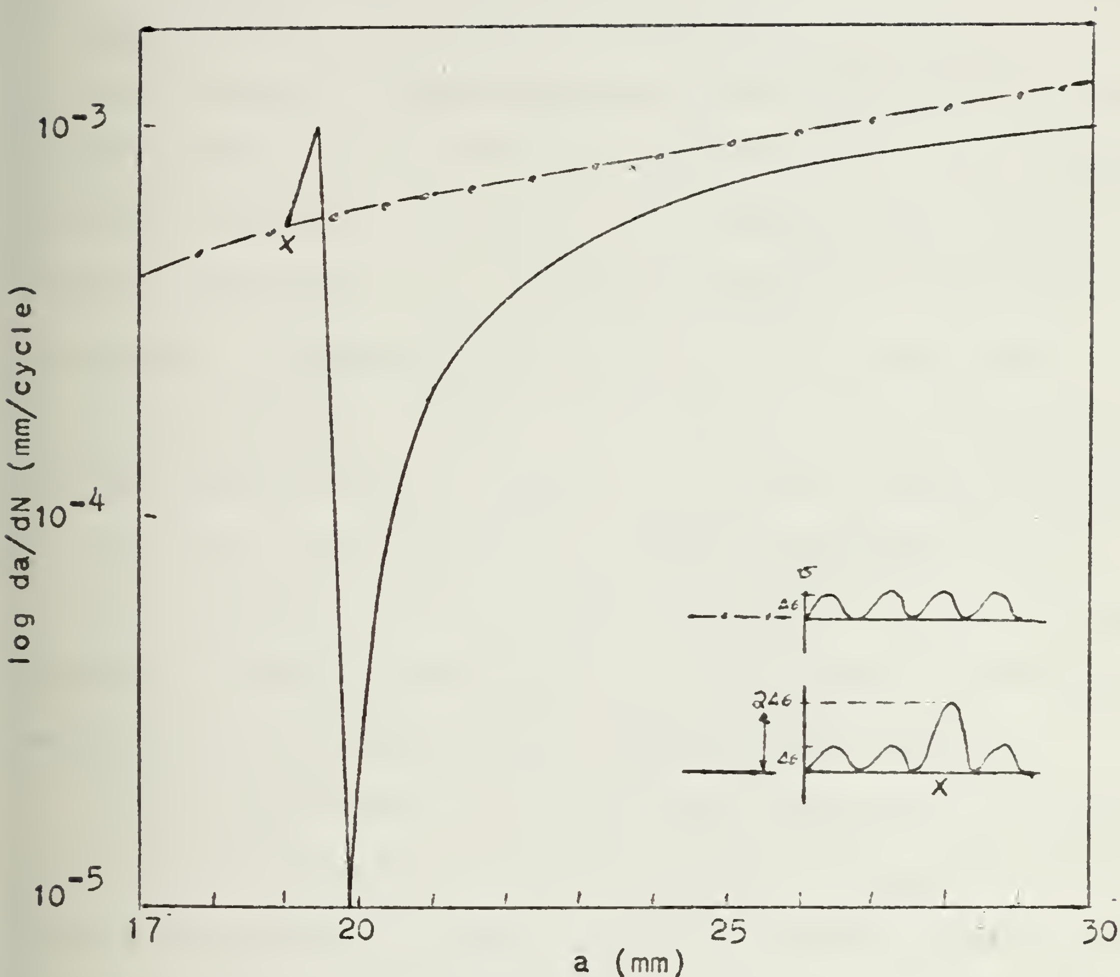


FIGURE 4-9. Effect of single high stress on subsequent crack propagation behaviour under a lower stress.

Although his approach is very interesting from an academic viewpoint, the concept and required calculations are quite complex and as such are of questionable value on a practical applications level.

4.2 General Yielding Fracture Mechanics

The foregoing discussions have dealt with linear elastic fracture mechanics concepts. As pointed out, these concepts are only valid when fracture occurs under a small scale yielding condition, i.e., yielding zone size at the crack tip is small compared with the crack size. Thus, when localized yielding occurs, as at stress concentrations and with welding residual stresses, or when the material toughness is too great to be measured by elastic techniques, it is necessary to employ the concepts of general yielding fracture mechanics (GYFM). GYFM allows for the extension of fracture mechanics analysis beyond the linear elastic regime.

Brittle fracture initiation under large scale yielding is common in ordinary structural steels. Attempts to make plane strain linear elastic fracture toughness tests on low strength steels (yield strength up to 90 KSI) in thicknesses of practical interest have, in practice, often yielded invalid results except at very low temperatures.[69]

In discussing the criterion for fracture initiation under large scale yielding, the crack opening displacement (COD) and plastic zone size (ρ^+) concepts will be described. For each of these concepts, brittle fracture is assumed to

initiate when a parameter defined by the concept reaches a critical value.

4.2.1 Crack Opening Displacement

As with linear elastic fracture mechanics, the application of general yielding fracture mechanics requires the measurement of a fracture toughness parameter under laboratory test conditions. In the crack opening displacement concept, this parameter is the critical COD to fracture and is generally denoted by the symbol δ_c. Thus, the fracture initiation criterion is expressed as

$$\delta_{max} = \delta_c \tag{4.21}$$

where δ_{max} = the maximum strain on the most dangerous defect

δ_c = the limit strain at fracture initiation

In order to assess the significance of a weld defect under conditions of general yielding, it is necessary to know the size, shape and orientation of the flaw, and the general stress field within which the defect is located. A relationship is also required which relates the applied load, defect size, and material properties and local conditions at the crack tip. With these factors defined, the flaw dimension, which will cause failure for various levels of applied stress and fracture toughness, can be determined. It has been shown that for the simple case of a through crack of length 2a in an infinite plate, the COD relationship is:[68,69]

$$\delta = \frac{8\ \sigma_y\ a}{\pi E}\ \log_e\ \operatorname{Sec}\left(\frac{\pi\sigma}{2\sigma_y}\right) \tag{4.22}$$

Since the strain at yield is (σ_y/E), equation (4.22) can be rewritten in terms of strain as:

$$\delta = \frac{8\ e_y\ a}{\pi}\ \log_e\ \operatorname{Sec}\left(\frac{\pi\sigma}{2\sigma_y}\right) \tag{4.23}$$

If the stress, σ, is specified as a function of the yield stress, σ_y, equation (4.23) reduces to:

$$\delta = \text{Constant}\ (e_y\ a) \quad \text{For}\ \frac{\sigma}{\sigma_y} < 1 \tag{4.24}$$

The maximum allowable defect size can thus be expressed as:

$$a_{cr} = \text{Constant}\ (\delta_c/e_y) \tag{4.25}$$

The constant in this expression depends upon the design stress and stress concentration values.

It should be noted that e_y in the above equations relates to the yield properties of the material controlling the plastic zone size. The appropriate value of e_y thus applies to the material at the tip of the crack. In a welded structure, this may be related to the weld metal or the heat affected zone properties.[68]

There has been much experimental work performed to verify the validity of the COD approach. The results of such experimentation have shown that measurements of δ_c from small specimens can be used to estimate the fracture strength of large specimens or actual structures.[44,45,10,50] A crack assessment based upon the measurement of δ_c provides a useful and convient method of predicting the brittle fracture initiation in structural components, subject to large scale yielding.

As with most concepts, COD is not immune to weaknesses. Like other fracture toughness parameters, δ_c is inherently dependent on several factors. In fact, a critical COD value cannot, in the strict sense, be considered a material constant, but rather must be regarded as a variable depending on various factors. The dependency of COD not only on temperature but also on mechanical factors such as notch acuity, strain rate, plastic constraint and plate thickness must be considered and accounted for in the application of the COD concept.

Temperature is one of the more dominant factors affecting the material toughness parameter δ_c. Koshiga[10,45] has shown that the temperature dependence of structural steels can be expressed as:

$$\delta_c = \alpha' \quad \sigma_{yT}\left(\frac{T}{100}\right)^5 \tag{4.26}$$

where α' = a constant for the given material

σ_{yT} = the yield stress at the temperature concerned

T = the absolute temperature

The critical COD has the same qualitative dependence on plate thickness as does the linear elastic parameter K_{1c}, i.e., δ_c decreases with increasing plate thickness.[45,37] This effect is less for δ_c than for K_{1c}. An example of the effect of plate thickness on δ_c is shown in Figure 4-10.[45]

Figure 4-11[45] shows the relationship between δ_c and notch tip acuity obtained from small tensile specimen tests with notches of various radii. As can be seen, the larger the notch tip radius, the larger the value of δ_c. Other experimental data has shown δ_c dependence on notch tip acuity to be different for different types of steels.[45]

Experimental tests have also demonstrated that there is a strong effect of plastic constraint on δ_c. As the intensity of plastic constraint is increased, the critical COD value is decreased.[45,50] The level of applied stress required to produce a given COD becomes larger as the degree of plastic constraint becomes larger.[45]

The fact that δ_c values obtained from Charpy type impact tests are much lower than those obtained from slow bend tests has substantiated the fact that δ_c is sensitive to strain rate. In applying COD concepts to structures which may experience impact loading, the rate of loading used in the tests must duplicate the loading rate as found in the actual service application.[45,46]

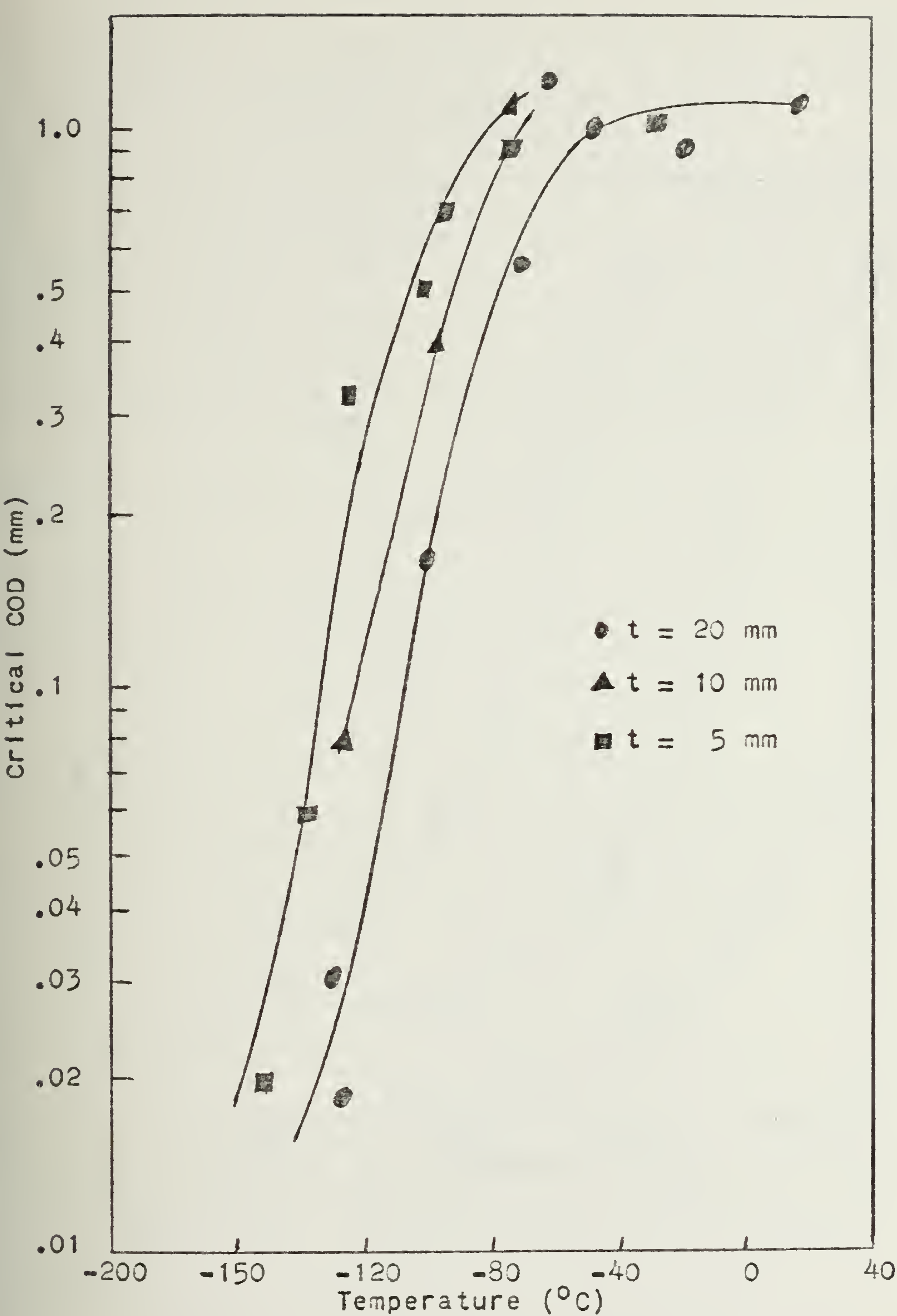


FIGURE 4-10. Plate thickness dependence of critical COD.

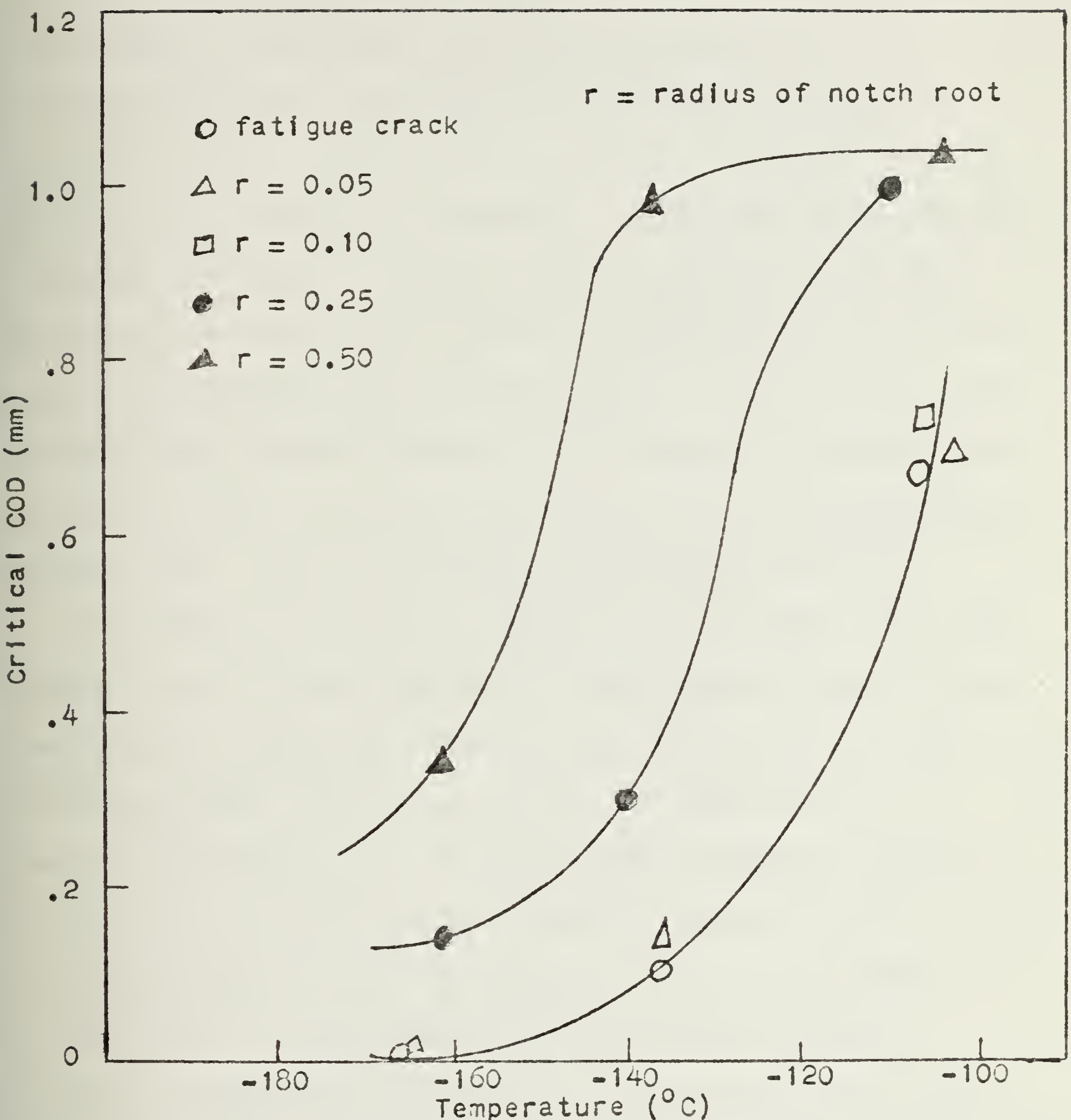


FIGURE 4-11. Effect of notch acuity on δ_c.

In welded structures, residual stresses will be developed which can approach a value corresponding to the yield stress of the base plate material. Since the test piece used for measuring the fracture toughness δ_c is normally cut from a large plate, the effect of residual stresses is lost. Under these conditions, the measured δ_c relates to the material toughness in the absence of residual stresses. In order to apply a COD value to an as-welded structure, the additional effect on the structure of yield point magnitude residual stresses must be considered. The effect of the residual stress is to produce an initial COD (δ_R) at the crack tip which contributes to the value of any measured COD. This is illustrated in Figure 4-12.[45]

Egan[68] has proposed a method of accounting for such stresses based on the assumption that elastic strain levels resulting from component stresses can be summed. In the as-welded joint, the crack tip will be subjected to an opening displacement due to the remotely applied stress, σ, and due to the local residual stress, assumed to be of yield stress magnitude. If it is further assumed that local yielding will be contained by the surrounding elastic material, a first approximation of the acting strain level that the crack tip experiences can be obtained by adding the elastic components of strain, $e + e_y$. Since this method assumes that the local yielding is contained, Egan states that under true elastic-plastic conditions, this procedure is over conservative since, in the elastic-plastic regime,

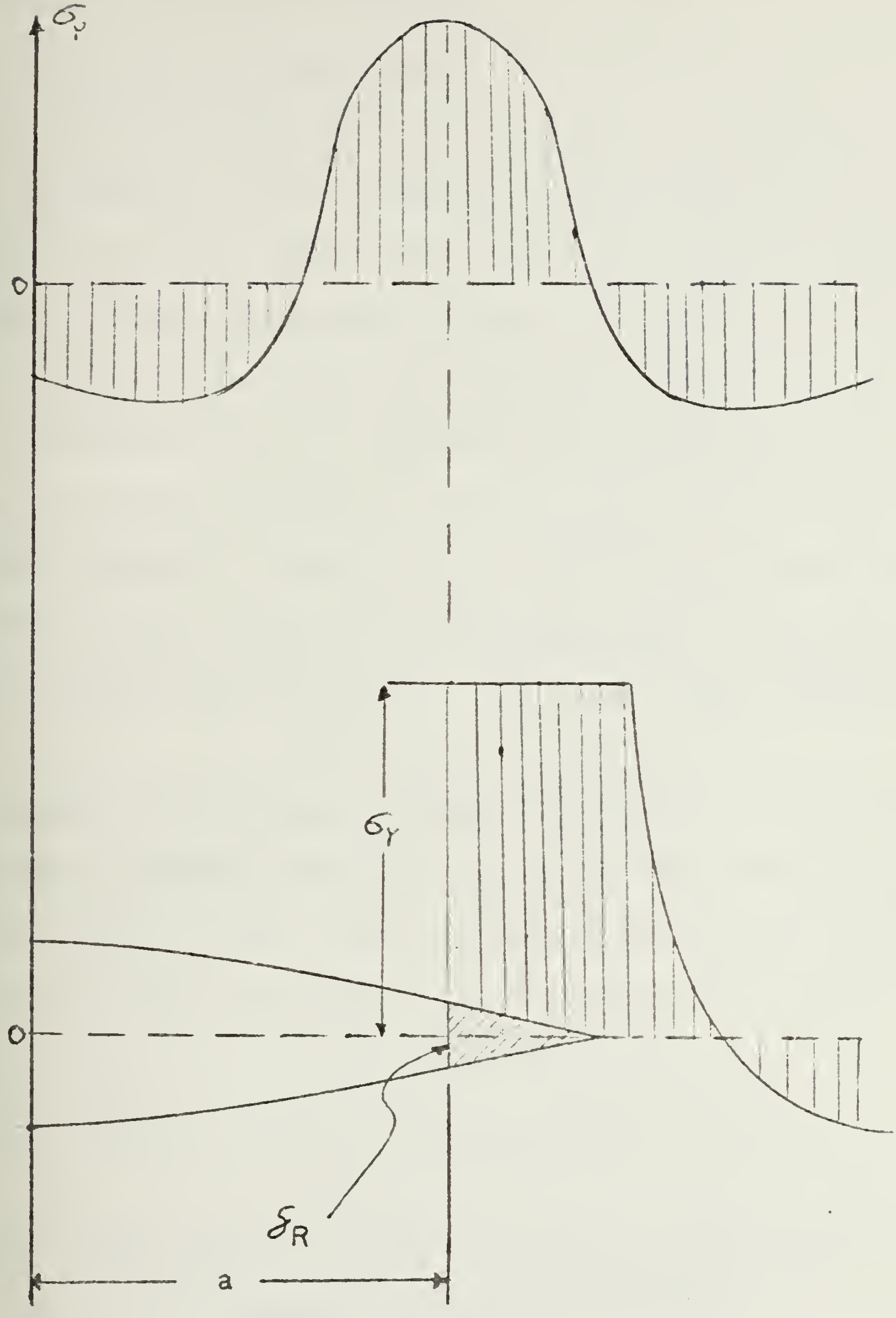


FIGURE 4-12. A crack in welding residual stress field.

appreciable crack tip plasticity will negate to some extent the effect of residual stresses.

4.2.2 Plastic Zone Size

It has been seen that in situations where the crack tip is surrounded by a well developed plastic zone, the COD concept can be used to evaluate the significance of weld defects. Another promising engineering concept of brittle fracture initiation under large scale yielding is that of plastic zone size (ρ^+). A graphic illustration of this concept is given in Figure 4-13.[49] The fracture criterion for this concept is based on the idea that brittle fracture initiation occurs when ρ^+ reaches the upper limit which can be sustained by the material. This upper limit is denoted by ρ_c^+.

Unlike the fracture toughness parameter δ_c which is a measurable quantity, the value of ρ_c^+ is not easily determined by direct measurement. The expression below given by Koshina[49] has proven useful in converting the measured δ_c to ρ_c^+.

$$\rho_c^+ = \left(\frac{\pi E}{8\sigma_y}\right) \delta_c \tag{4.27}$$

The temperature dependence of ρ_c^+ has been found to follow a simple emperical expression:[49,10]

$$\rho_c^+ = \alpha\left(\frac{T}{100}\right)^5 \tag{4.28}$$

where T is the absolute temperature and α is a material constant.

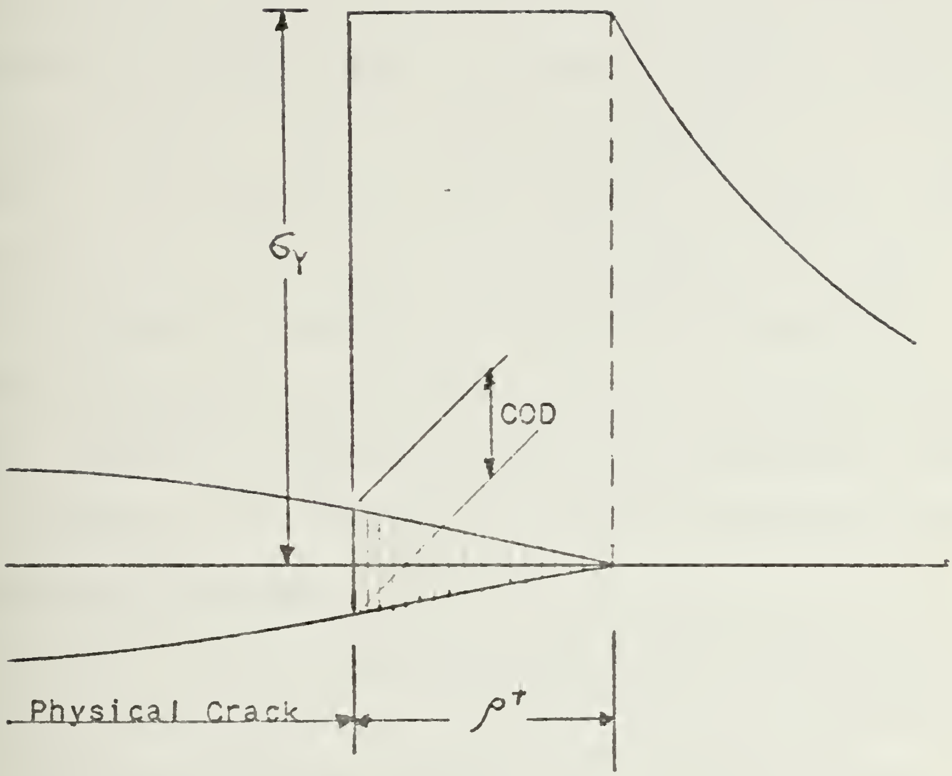


FIGURE 4-13. Plastic zone size ρ^+.

The plastic zone size concept is useful in circumventing a problem experienced when the COD concept is applied to situations where the structure has been pre-loaded. It is found that due to the irreversible deformation around the crack tip resulting from the preloading, the crack will sustain a certain amount of residual COD. This residual COD is maintained even after the load is removed. Under such conditions, the COD loses its physical meaning as an engineering parameter. The plastic zone size, which is usually computed from established crack models (Dugdale model for example), is not influenced by the existance of the residual COD.[45]

The ρ_c^+ concept has been successful in predicting the fracture stress of a component and it is especially useful when conditions of preloading and residual stresses exist.[49,45,10]

4.3 Concept Comparison

Under the simple conditions where the plastic zone size at the crack tip is small in relation to the crack size, the three fracture initiation criteria K_{1c}, δ_c and ρ_c^+ are equivalent.[44] This occurs because the three quantities are related by the following expressions:

$$\delta_c \simeq K_{1c}{}^2/E\,\sigma_y \qquad (4.29)$$

$$\rho_c^+ \simeq K_{1c}{}^2/\sigma_y{}^2 \qquad \text{for } \sigma \lesssim .6\sigma_y \qquad (4.30)$$

For conditions of large scale plastic yielding, the applicability of K_{1c} is clearly not acceptable since it is based on linear elastic theory.

In the presence of residual stresses or preloading, care must be taken when determining which criteria should apply. The equivalence of the three criteria no longer holds when residual stresses and preloading are introduced even if small plastic zone size conditions are maintained. In their own areas of applicability, each criterion can be manipulated to account for the presence of welding residual stresses. For a preloaded cracked structure, however, the K_{1c} concept cannot be applied. This is the case because the residual stress, caused by the preloading, is inherently associated with the crack tip plastic deformation, which cannot be incorporated in the value of K_{1c}. For an analysis of a structure experiencing preloading, it may be advantageous to employ the plastic zone size concept instead of the COD criterion.

The salient features of the three criteria are summarized in Table 4-1.[45]

TABLE 4-1. Salient Features of Three Criteria

Item	Criterion		
	K_c	ρ_c^+	δ_c
The range of application	Only applicable to small scale yielding	Not applicable after general yielding	All ranges
Measurement	Quite simple	Difficult and cumbersome	Simple
Calculation of σ_f with residual stress or preloading	Inadequate		Adequate
Calculation Procedure	Complex	Quite easy	Rather easy
Calculating principle	Ambiguous	Clear	Somewhat ambiguous

CHAPTER 5

WELD DEFECT ASSESSMENT AND THE ENVIRONMENT

5.1 General

All welded structures exist and function under certain environmental conditions. This may range from relatively neutral environments such as dry air to more aggressive environments such as sea water. The material characteristics and the environment combine to determine if the integrity of the structure will be jeopardized due to premature failure resulting from cracking induced by aggressive environments.

The existance of environment induced cracking (stress corrosion cracking-SCC) first became of technological importance in the 19th century, with the adoption of cold-drawn brass cartridge cases.[59] Since then, stress corrosion cracking has been observed in many materials under a wide range of environments. Today, it can be said that stress corrosion cracking is a general phenomenon which, when given the wrong combination of material characteristics and environment, can be experienced by any alloy family.

Steels, particularly the high strength steels, are susceptible to stress corrosion cracking and, for reasons discussed later, welded steel structures are even more likely to fail due to environment induced cracking. These factors make it important to understand how stress corrosion cracking affects a given material and necessitates the development of failure criteria which reflect the effects of aggressive environments.

Stress corrosion cracking is a cracking process characterized by the joint action of stress and corrodent. The following characteristics are representative of most, if not all, stress corrosion cracking situations.[59]

1. The existance of tensile stress is a necessary condition. Such stress can be produced by cold working, stored as residual stress, or be externally applied service stress.
2. The alloy, under most circumstances, is inert to the environment which causes cracking. An exception to this is high strength steel which may experience general rusting at the same time it is cracking.
3. Only particular combinations of alloys and environments produce SCC.
4. The necessary corrodent need not be present in high concentrations or in large quantities.
5. Stress corrosion cracks are brittle in macroscopic appearance even though the metal may behave in a highly ductile manner in purely mechanical fracture.
6. Stress corrosion fracture mode is usually very different from the purely mechanical plane strain separation mode of fracture.
7. In many systems there appears to be a threshold stress or stress intensity below which SCC does not occur.

8. Stress corrosion cracking does not occur in pure metals.

A multitude of theories and models have been proposed to describe the mechanisms involved in the stress corrosion process. Information on such theories and other general SCC considerations are readily available in the literature[63,59] and will not be discussed in detail here. The one fact to keep in mind is that stress corrosion cracking is a phenomenon which is controlled by the metallurgy of the material, the chemistry of the environment, and the stress field.[59]

5.2 Stress Corrosion Cracking Susceptibility

With regard to steels, stress corrosion cracking susceptibility increases as the yield strength or hardness increases.[57,59] SCC thus assumes particular significance in the case of high strength alloys.

As noted earlier, welded joints in high strength steels tend to be especially susceptable to stress corrosion cracking. In the as-welded condition, residual welding stresses will be present. In the weld area these stresses will be tensile, and normally of yield stress magnitude. The existance of such high stresses can significantly increase the risk of environment induced cracking. Another problem experienced with some welded joint designs, is the presence of crevices which provide areas where concentrations of aggressive chemicals can accumulate. Such locations provide excellent conditions under which stress corrosion cracking can occur. Metallurgical changes, occurring during

the welding thermal cycle, may result in local microstructures that are particularly susceptable to SCC. All these factors contribute to a lowering of the resistance of the welded joint to attack by stress corrosion cracking. This will be the case even though the base metal may be relatively immune to SCC.

In a recent study by Gooch,[57] the SCC behavior of various welded steel joints was investigated. The following conclusions were drawn:

1. The susceptibility of welded high strength steels to SCC is primarily dependent on the microstructure present in the different weld areas. The susceptibility generally increases as the hardness of the area increases. In medium carbon steels, for instance, considerable loss in SCC resistance occurred in the HAZ, due to the high degree of hardness which developed in this area during the welding thermal cycle. The presence of twinned martensite was also noted as having a strong effect in lowering SCC resistance.
2. SCC can take place inter-granularly or transgranularly.
3. Of the alloys studied (five high strength steels - medium carbon, low alloy and low carbon, precipitation hardening grades), the highest SCC resistance was found with

the low carbon precipitation hardening steels. Medium carbon, low alloy steels tempered at high temperatures to similar hardnesses were found to exhibit comparable resistance to SCC.

4. The presence of alloy element segregation and inclusions can reduce the SCC resistance of high strength steel weld metal. These effects are, however, of secondary importance to those of microstructure.

5. Stress corrosion cracking will not occur in structural steels exposed to a marine environment if the hardness of the steel is less than a hardness value of 450HV. This value is taken as 400HV for high strength steels.

5.3 Failure Criteria Based on Linear Elastic Fracture Mechanics

The effect of an aggressive environment is something that cannot be ignored when one is assessing the significance of weld defects in welded steel structures. Currently, failure criteria which include considerations for premature failure resulting from environment induced cracking are either non-existant, emperical in nature, or highly over-simplified and of questionable value.[58]

Thus far in this paper, it has been shown that fracture mechanics concepts can be utilized as a basis for failure criteria for materials in non-aggressive environments. It is logical, therefore, to take an approach toward developing

similar criteria for materials in aggressive environments based on an expansion of these previously developed concepts.

For the important case of high strength steels, linear elastic fracture mechanics concepts apply and will thus be the basis for the development of failure criteria.

The fracture mechanics stress intensity factor K_1 is relevant to stress corrosion cracking because the undefined stress and strain conditions at the crack tip are caused by the elastic field quantified by K_1. Thus, if a given K_1 level is found to cause stress corrosion crack extension, then any combination of component geometry, geometry of crack and stress which duplicates this given K_1 level will also duplicate the stress corrosion crack extension. The material and the environment for which the given K_1 level was established must be the same as that for the actual structure under investigation.

In the non-aggressive environment case, a specific K_1 level, called K_{1c}, was defined as the critical stress intensity level at the tip of a crack necessary for immediate catastrophic failure. In a like manner, a stress intensity factor, K_{1scc}, can be defined to describe material behavior in situations where, due to aggressive environments, subcritical crack growth preceeds catastrophic fracture. K_{1scc} is termed the "threshold" stress intensity level and represents the K_1 level above which stress corrosion crack growth has been observed, but below which it has not been observed.

In general, the effect of K_1 on SCC kinetics is shown in Figure 5-1.[59] From the figure we see that in Region I the log of crack growth is approximately linearly proportional to K_1. The crack growth behavior in this region is believed to be controlled by combined chemical and mechanical forces leading to cracking.[58] In Region II of the figure, the crack growth rate becomes independent of K_1. The behavior in this region is thought to result from transport controlled crack growth.[58] With still higher K_1 levels, a K_1-dependent crack growth rate (Region III) is again observed, resulting from pure mechanical separation.

Because stress intensities in Region III are very near the value of fracture toughness K_{1c}, crack growth rates in this region are assumed to be very rapid for all environments, therefore, this region is not of primary interest in environmental discussions.

Williams[58] has shown that the crack growth rate is determined by the slower of the two rate processes, in Region I and Region II, operating in series. The total crack growth rate is thus given by:

$$\frac{1}{(da/dt)} = \frac{1}{\dot{R}_I} + \frac{1}{\dot{R}_{II}} \tag{5.1}$$

or

$$da/dt = \frac{\dot{R}_I \, \dot{R}_{II}}{\dot{R}_I + \dot{R}_{II}} \tag{5.2}$$

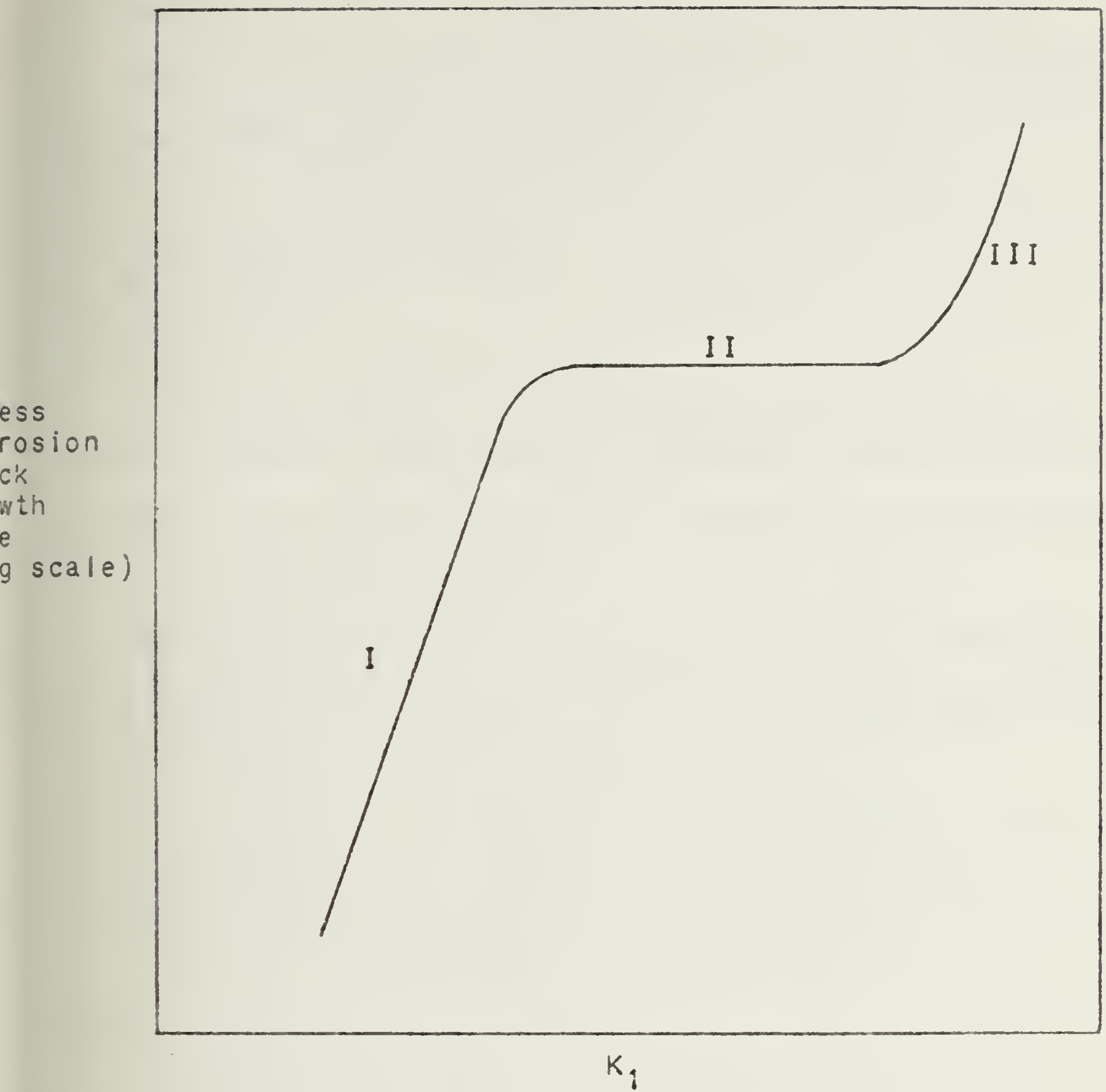


FIGURE 5-1. Generalized SCC kinetics.

where da/dt is the total crack growth rate and $\dot{R}_I$ and $\dot{R}_{II}$ represent the rates in Regions I and II respectively.

Equation (5.2) can be integrated to give an expression for the crack length, a, as a function of time:

$$\int_{a_o}^{a} \frac{\dot{R}_I + \dot{R}_{II}}{\dot{R}_I \, \dot{R}_{II}} = \int_o^t dt \qquad (5.3)$$

Later on, it will be seen how information on crack length variation with time is useful for establishing design criteria for materials which are susceptable to environment induced crack growth.

To further expand these fracture mechanics concepts, let's assume we have a semi-elliptical surface defect which has an expression for K_1 given by:

$$K_1^2 = \frac{1.21 \; a \; \pi \; \sigma^2}{Q} \qquad (5.4)$$

Again $\quad$ a = the crack depth

σ = the stress

Q = the flaw shape parameter

Solving equation (5.4) for the crack depth a:

$$a = \frac{K_1^2 \; Q}{1.21 \; \pi \; \sigma^2} \qquad (5.5)$$

If we further assume a long, thin flaw and the existance of yield point stress, equation (5.5) becomes:

$$a = .2(K_1/\sigma_y)^2 \tag{5.6}$$

When the K_1 level reaches K_{1scc} we can expect stress corrosion crack propagation. The depth of flaw which must be exceeded for stress corrosion propagation is therefore given by:

$$a_{cr} = .2\left(\frac{K_{1scc}}{\sigma_y}\right)^2 \tag{5.7}$$

This critical crack size can be looked upon as a figure of merit which incorporates both the SCC resistance (K_{1scc}) of the metal and the contribution which yield strength stress levels, resulting from residual or fit-up stresses, make to SCC hazard. The SCC characteristics of a material can be expressed if equation (5.7) is plotted for various values of critical crack size. This is shown in Figure 5-2[59] for a_{cr}=.1 IN and a_{cr}=.01 IN.

Figures like 5-2 can be utilized in several ways. If a material is found to have a K_{1scc}, as indicated by point X, a surface crack .1 IN deep would be deeper than required to propagate a stress corrosion crack in the same environment used to determine K_{1scc}. A crack .01 IN deep, however, would not propagate a stress corrosion crack in the same material under the same environmental conditions.

Looking at the figure in a different way, if it is known that our NDT procedures can only detect a flaw larger

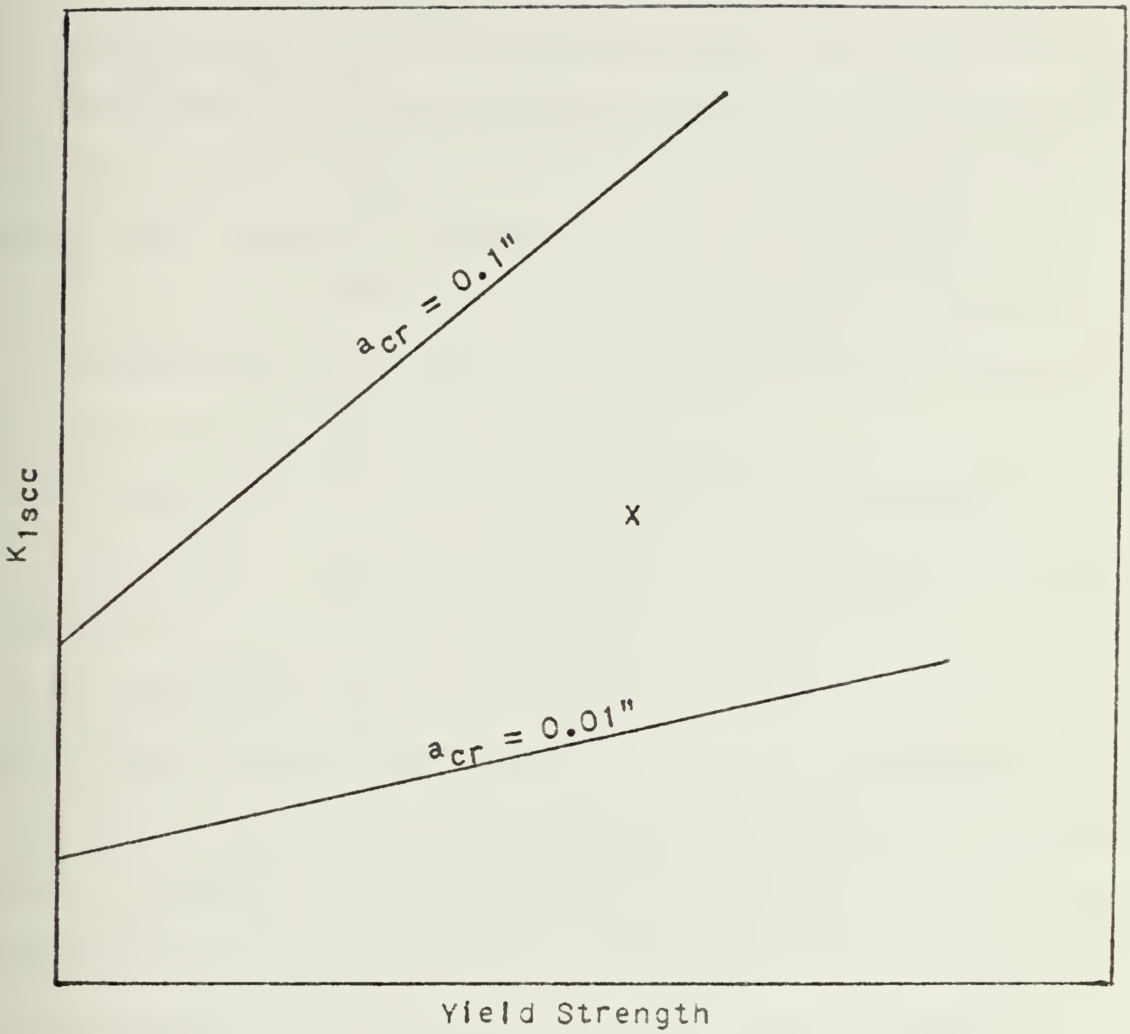


FIGURE 5-2. Plot of Equation (5.7) for two assumed values of a_{cr}, assuming long surface flaws and yield strength stresses operating.

than .01 IN deep, then at yield strength stress levels, Figure 5-2 tells us that the material used must have a K_{1scc} above the .01 IN line.

Because K_{1scc} values are always lower than K_{1c} values, it is sometimes said that corrosion has reduced the fracture toughness of the material. Technically, this is not true because there has been no demonstrated effect of chemical environment on K_{1c}.[59] Instead of lowering the value of K_{1c}, corrosion acts to promote a different fracture process (SCC) at a lower level of K_1.

A summary of data on the K_{1scc} values for selected steels and welds in water, salt water and sea water is given in Appendix B.

The employment of K_{1scc} values to assess the significance of weld defects under conditions of an aggressive environment can be useful and convenient. There is, however, a danger in using K_{1scc} data which must be kept in mind. As discussed earlier, K_{1scc} is the "threshold" stress intensity for crack growth initiation. The caveat lies in the fact that there is no way to be sure that the measured value of K_{1scc} is indeed the true "threshold" stress intensity. In some cases we may, in fact, obtain the true "threshold" stress intensity for crack initiation, but at present, there is no direct way of determining when this is the case.[58,59]

K_{1scc} is not nearly as well defined or as definable as is K_{1c}. In fact, K_{1scc} must not be considered a material property, since it is a function of measurement sensitivity,

the material, and the environment. Furthermore, there are indications that it may also be dependent on time, temperature and stress state.[58]

The use of K_{1scc} in equations like equation (5.7) could constitute a non-realistic design criterion if the problem under investigation had conditions which were not identical to those for which the K_{1scc} value was determined.

In a work by Williams,[58] a new approach to establishing realistic design criteria for components subject to environment induced crack growth was introduced. It is based on fracture mechanics analysis in conjunction with the relationship expressed in equation (5.3). It does not depend on the use of a specific value of "threshold" stress intensity, K_{1scc}.

From Figure 5-1, the crack growth rates in Regions I and II can be written as:

$$\dot{R}_I = f(K_1) = C_1 \, e^{m_1 k_1} \tag{5.8}$$

$$\dot{R}_{II} = C_2; \; \frac{\partial \dot{R}_{II}}{\partial K_1} = 0 \tag{5.9}$$

In these relationships, C_1, m_1 and C_2 are undefined parameters which are independent of K_1 (and thus a) but which may depend on temperature and other environmental variables.

From earlier discussions, the general form of the stress intensity solution was given by:

$$K_1 = M\sigma \left(\frac{\pi a}{Q}\right)^{1/2} \tag{4.1}$$

Using equation (4.1), equation (5.8) can be rewritten as:

$$\dot{R}_I = C_1 \, e^{[m_1 \sigma M (\frac{\pi a}{Q})^{1/2}]} = C_1 \, e^{\sigma \phi a^{1/2}} \tag{5.10}$$

where $\phi = m_1 M (\frac{\pi}{Q})^{1/2}$

Now making use of equation (5.2), equation (5.9) and equation (5.10) we have:

$$da/dt = \frac{C_1 e^{\sigma\phi a^{1/2}} \quad C_2}{C_1 e^{\sigma\phi a^{1/2}} + C_2} \tag{5.11}$$

or

$$\int_{a_o}^{a} \frac{C_1 e^{\sigma\phi a^{1/2}} + C_2}{C_1 e^{\sigma\phi a^{1/2}} \quad C_2} = \int_{o}^{t} dt \tag{5.12}$$

If it is now assumed that Q, and therefore ϕ, is independent of a, equation (5.12) can be solved to obtain:

$$t = \frac{a-a_o}{C_2} - \frac{2}{C_2 \sigma^2 \phi^2} \left(\frac{\sigma\phi a^{1/2}+1}{e^{\sigma\phi a^{1/2}}} - \frac{\sigma\phi a_o^{1/2}+1}{e^{\sigma\phi a_o^{1/2}}}\right) \tag{5.13}$$

We thus have an expression which can be used to calculate the failure time resulting from environment induced cracking. The instantaneous crack length, a, for any specified time of exposure, t, and initial crack length, a_o, can also be obtained from equation (5.13).

Perhaps a more useful parameter which can be calculated from equation (5.13) is $(a_o/a_{cr})^{1/2}$. This parameter can be shown to equal K_1/K_{1c}. Given the specific form and value of the constants in the general relation of equation (5.13) (determined by experiment) and the values of K_{1c} and a_{cr}, the parameter (K_1/K_{1c}) can be calculated, as a function of the failure time, for a given initial stress intensity K_1 or a given initial crack length a_o. For illustrative purposes, (K_1/K_{1c}) for hydrogen-induced crack growth in Ti-5Al-2.5Sn is plotted versus time for various temperatures in Figure 5-3.[58]

The specific form of equation (5.13) which resulted for the Ti-5Al-2.5Sn alloy was a function of temperature, thus (K_1/K_{1c}) was a strong function of both time and temperature.

The information available from relations like those depicted in Figure 5-3 can be very useful. For example, the initial stress intensity of a component required to have a service life of 60 minutes for a specified environment and stress condition must be less than .28 x K_{1c} at a temperature of 24° C.

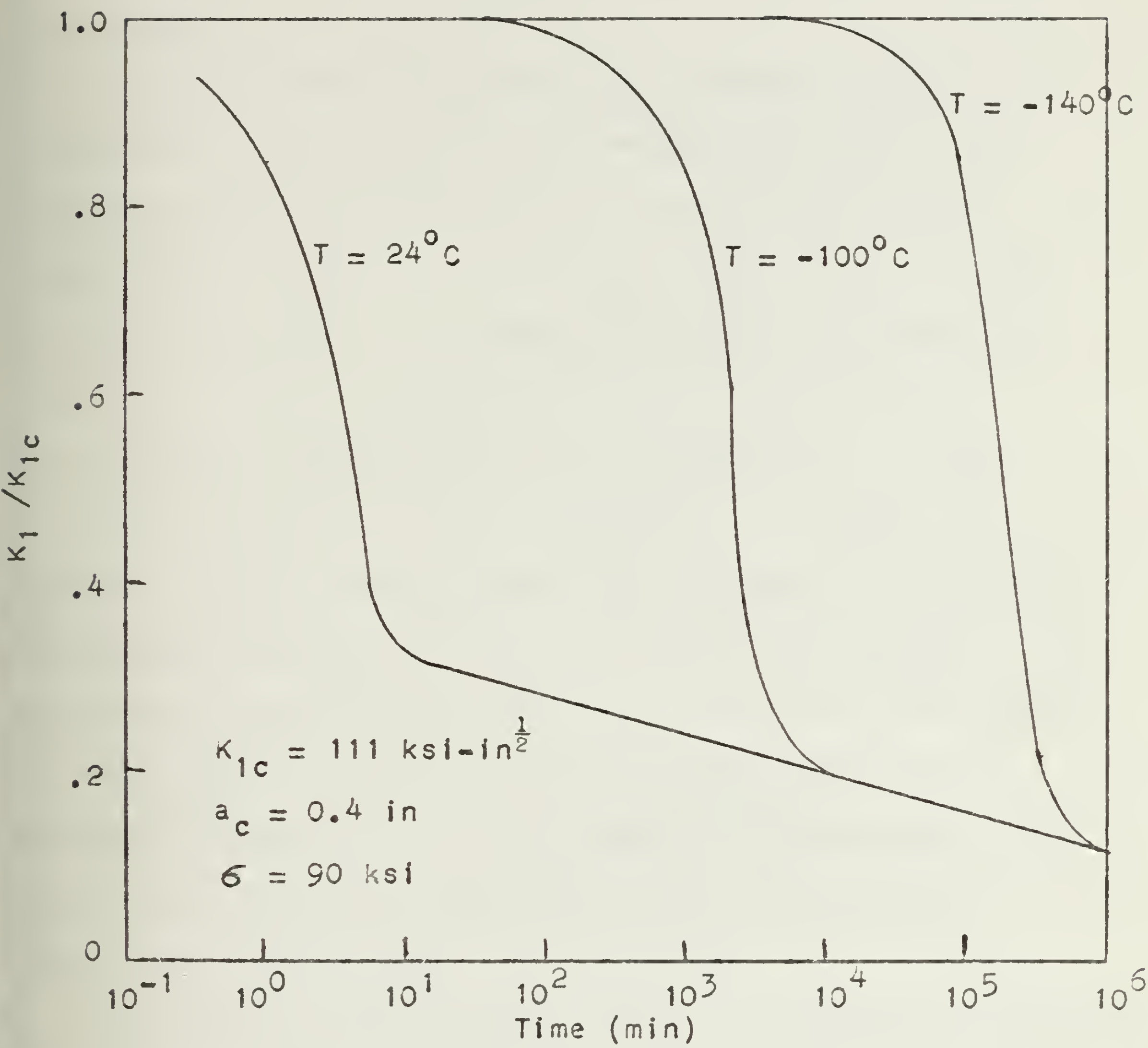


FIGURE 5-3. Analytically predicted relationship between the normalized stress intensity and failure time for Ti-5Al-2.5Sn at three temperatures.

CHAPTER 6

UTILIZATION OF FRACTURE MECHANICS CONCEPTS

6.1 General

In the foregoing chapters, the various types of weld defects and their effect on the welded structure, the detection ability of current non-destructive testing techniques and existing weld defect acceptance standards have been discussed. The assessment of weld defects was considered based on fracture mechanics analysis and environmental considerations were introduced. In the remainder of Part I, these individual areas shall be brought together and developed into a system of weld defect assessment which is of practical use to the engineer. The discussion which follows shall deal with the total concept of weld defect assessment based upon the "fitness for purpose" philosophy. The need for such an analysis and its application to pratical problems and to weld defect acceptance standards will be discussed.

The primary goal of the "fitness for purpose" philosophy is to provide welded structures which are safe from brittle fracture during their service life. This is to be accomplished with a minimum of repair welding resulting from the presence of weld defects.

6.2 Need

There is evidence that there exists a need for fracture prevention techniques beyond the traditional engineering practice. Many plant failures, by partial or complete

fracture, are still occurring during fabrication, while the structure is undergoing required pressure tests or upon being placed into service.[71] Even in the light of such failures, people still question the need for new techniques. They feel that the traditional Charpy V-notch tests, for example, are effective in many applications and there is no need for additional fracture prevention techniques. Nichols[71] and other authors have pointed out that the Charpy value that must be specified to prevent failure depends on the thickness, strength level, alloy content, applied stress and rate of loading. It can therefore be dangerous to use a particular Charpy specification outside the range of conditions for which it was derived. Under some circumstances, the Charpy V-notch test has even rated materials in the wrong order of resistance to fracture.[71]

The Charpy approach also suffers from the fact that it is non-quantitative with respect to permissible stress levels and defect sizes.

The rationale behind the continued reliance on established weld defect acceptance standards is currently being questioned on many fronts. With more defects being detected due to the growing sensitivity of non-destructive test techniques, and with the increasing costs and risks associated with the removal and repair of weld defects, an emphasis toward an assessment of weld defects based on fitness for purpose of the structure is emerging. It is also being discovered that a more rigorous approach is needed when it must be

unquestionably demonstrated that the risk of failure due to brittle fracture is minimal. This is particularly true in the field of nuclear reactor pressure vessels. A similar rigorous approach is required for assessing the significance of defects detected in components already in service.

It must also be realized that welded structures have an inherent strength, even in the presence of weld defects. It is only reasonable that an optimum allowable defect size be determined on a rational basis with due consideration to the factors of safety and economy. It is clear that the estimation of the defect size at which repair welding is appropriate can lead to considerable economic savings.

In summary, advancing technology has precipitated a demand for more fundamental, quantitative, and rational design procedures in the presence of weld defects.

6.3 Practical Applications

Fracture mechanics concepts have been developed in recent years to the point where they are of direct engineering value for the prevention of brittle fracture of welded structures. One of the by-products achieved through fracture mechanics analysis is that it forces an inter-displinary, systems type approach, to failure prevention. In using the technology, it is necessary to account for the interactions between material properties, design, fabrication, inspection, and operational requirements. With the appropriate information in the related areas of material properties, stresses and potential or existing weld defects, fracture

mechanics can be employed to ensure that the desired degree of immunity from brittle fracture is achieved.

The total systems type approach to fracture prevention will be developed further in Part II.

The overriding question in the area of defect assessment is what defect tolerance level is allowable without impairing the soundness of the structure. The determination of a tolerance level rests on an assessment of the significance of a weld defect. This assessment is not necessarily a straight forward matter. There is much that must be known before a fracture mechanics analysis can be performed. Data on loading conditions, environment, material and geometry of the part, the size, location and nature of the defect, the existance of stress concentrations and the nature of residual stresses must all be available. Nevertheless, with the development of the fracture mechanics approach to the analysis of brittle fracture, one is in a much better position to assess the significance of a weld defect and to answer the nagging questions related to the establishment of weld defect tolerance limits.

A very important requirement for fracture mechanics analysis is accurate information on the defect itself. It is in providing such data, that NDT methods play such an important role. Accurate information on location, size, shape, orientation and distribution of defects is vital.

In the case of multiple defects, their orientation and distribution may require that the entire cluster of defects be treated as a single defect.

During the general discussions on fracture mechanics concepts, expressions for maximum allowable flaw size were obtained. The NDT procedure used to inspect a weld must be tailored to this dimension. The inspection technique must be capable of detecting defects that are smaller in size than that which the analysis has indicated can be tolerated.

Assuming that the required information on stresses, defects, and material properties is available, the fracture mechanics concept can be used to establish step-by-step procedures to assess the significance of a weld defect. A generalized procedure will now be developed for welded structures with crack or crack-like weld defects. The object of the procedure is to establish whether the available material properties, stresses, and inspection techniques are sufficiently compatible to provide the desired immunity from brittle fracture.

The first decision which must be made is what type of analysis is applicable to the given problem. If the material can satisfy the plain strain conditions required in linear elastic analysis, then it would be best to use this concept. If, on the other hand, there is evidence that large scale yielding is possible, a general yielding fracture mechanics approach must be employed. It should be noted that GYFM concepts can be applied to the LEFM regime, but the reverse is not true.

For the purpose of this development, it will be assumed that LEFM analysis is appropriate. Both concepts do, however, follow similar procedures in their application.

After the existing or probable defect has been defined, a K_1 expression must be selected which will best model the defect-component geometry and loading conditions.

The failure condition must next be established. The structure will fail by brittle fracture when the prevailing K_1 level reaches K_{1c}. Therefore, the value of K_{1c}, for the material and environmental conditions under which the component operates, must be obtained. K_{1c} data is readily available and is expanding to take in more materials. With K_{1c} known, the critical defect size for failure (a_{cr}) can be determined from the rearranged equation for K_1 (see equation (4.2)).

If the structure does not undergo cyclic loading, the maximum allowable defect size can be compared with existing cracks to determine if they are acceptable or must be removed. The critical defect size can also be compared with available inspection limits to verify that the selected NDT procedures are adequate to detect a crack smaller than the critical size.

Any possibility of environment induced crack growth should be investigated at this point.

Additional steps must be carried out for structures which experience cyclic loading. The extent of crack growth over the life of the structure must be evaluated. Through

the use of a general cyclic life expression, the size of an initial crack which will grow to the critical size, due to the cyclic loading, can be determined. In this case, it is the initial tolerable defect size which must be compared with existing cracks or with the inspection limits. This procedure for defect assessment is illustrated schematically in Figure 6-1.[66]

Extensive work has been done in defining expressions for the critical defect size that can be readily applied to practical situations. Burdekin et.al.[69] have proposed that stress and crack size be represented by equivalent values, so that simple infinite plate relationships can be used in defining the critical crack size. As an example, for conditions of stress concentrations at the crack, the applied stress would be increased to a value given by the nominal stress multiplied by some stress concentration factor. For the crack dimension (a), an interpretation based on the crack configuration is used. The symbol $\bar{a}$ is introduced to represent this interpretated crack dimension.

The dominant dimension for surface or embedded cracks is height or depth, with the length being of secondary importance. However, with through thickness cracks, the length is the dominant parameter. For application purposes, Burdekin et.al. introduces the following simplifications. When a surface crack penetrates more than 70% through the thickness, the crack is treated as a full thickness crack with the parameter $\bar{a}$ taken as half crack length. Embedded

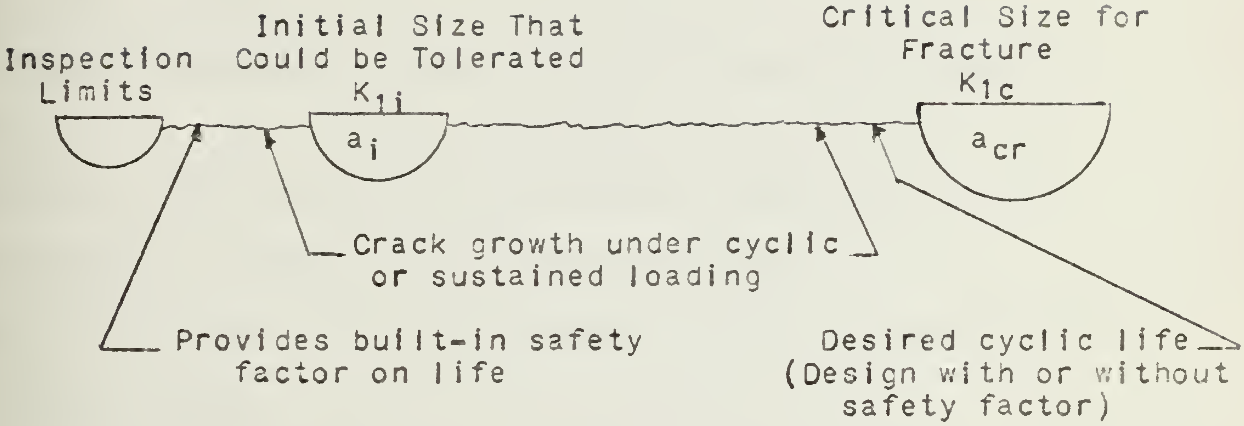


FIGURE 6-1. Schematic diagram of various defect sizes of concern in fracture mechanics analysis.

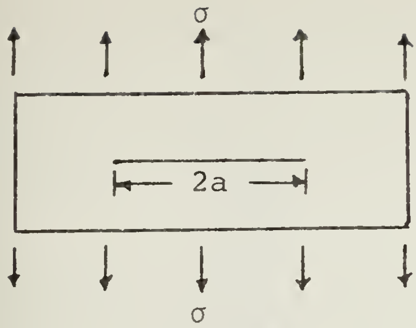
cracks are treated as opening to the surface if they approach within 15% of the thickness to either surface. The parameter $\bar{a}$, in this case, is the full crack height. Embedded cracks whose height exceeds 70% of the thickness are considered through thickness cracks with $\bar{a}$ taken as half crack length. These interpretations for the parameter $\bar{a}$ are summarized in Figure 6-2.[69]

Specific expressions for $\bar{a}_{cr}$ were then presented for use with pressure vessels. These relationships are given in Table 6-1.

With a knowledge of the fracture toughness (in terms of either COD or K_{1c}), a maximum permissible flaw size can be determined, for the acting stress level, using these simple expressions. In making use of the expressions given in Table 6-1 for the analysis of pressure vessels, the following assumptions apply:

1. The elastic components of stress can be summed and equated to strain.
2. The parameters (δ_c/e_y) and $(K_{1c}/\sigma_y)^2$ are considered to be equivalent measures of defect tolerance for all values.
3. The design stress/yield stress is 2/3.

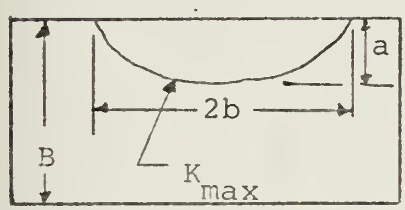
Egan[68] has expanded on this approach to include cases where the applied stress is greater than yield level stress. This condition may result from the action of residual stresses and stress concentrations.



Infinite plate $K_1 = \sigma\sqrt{\pi a}$

crack through thickness and remote from boundary-

Take $\bar{a}$ = half crack length



Surface crack

$$K_{max} = \frac{[1+.12(1-a/b)]\sigma\sqrt{\pi a}}{\phi_o}$$

1) For $a/B \le 0.7$, $b/B \le 5$

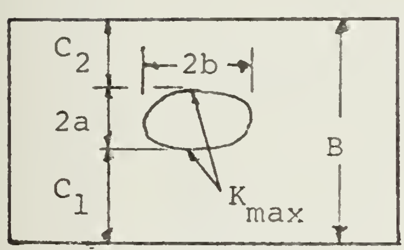
   take $\bar{a}$ = crack height

2) For $b/B > 5$

   take $\bar{a}$ = crack height
   $a/B \ngtr .3$ (2/3 yield design)

3) For $a/B \ge .7$, $b/B \le 5$

   take $\bar{a}$ = b = half crack length
   $K_{max} = 1.2\sigma\sqrt{\pi a}$



Embedded crack

$K_{max} = \sigma\sqrt{\pi a}/\phi_o$

1) For $2a/B \le .7$, $b/B \le 5$
   $C_1, C_2 > .15B$

   take $\bar{a}$ = half crack height

   $K_{max} = 1.2\sigma\sqrt{\pi a}$

2) For $b/B > 5$

   take $\bar{a}$ = half crack height
   $2a/B \ngtr .3$

3) For $2a/B \le .7$, $b/B \le 5$
   C_1 or $C_2 < .15B$
   take $\bar{a}$ = crack height

   $K_{max} = 1.2\sigma\sqrt{\pi a}$

4) For $2a/B \ge .7$, $b/B \le 5$

   take $\bar{a}$ = b = half crack length
   $K_{max} = 1.2\sigma\sqrt{\pi a}$

FIGURE 6-2. Alternative crack configurations and interpretations for parameter $\bar{a}$.

TABLE 6-1

EXPRESSIONS FOR $\bar{a}_{cr}$ (PRESSURE VESSELS)

	Main Pressure Vessel Shell No Residual Stresses	Main Pressure Vessel Shell with Stress Concentration (No Residual Stresses)	Main Pressure Vessel Shell with Residual Stresses
LEFM	$\bar{a}_{cr} = .5(\frac{K_{1c}}{\sigma_y})^2$	$\bar{a}_{cr} = .09(\frac{K_{1c}}{\sigma_y})^2$	$\bar{a}_{cr} = .09(\frac{K_{1c}}{\sigma_y})^2$
GYFM	$\bar{a}_{cr} = .5(\delta_c/e_y)$	$\bar{a}_{cr} = .09(\delta_c/e_y)$	$\bar{a}_{cr} = .09(\delta_c/e_y)$

The procedure set forward makes use of an experimentally determined relationship between a non-dimensional COD, designated as ϕ, and e/e_y. The parameter ϕ is given by:

$$\phi = \delta/2\pi e_y a \tag{6.1}$$

The form of the relationship is shown in Figure 6-3.[68]

The first step in the analysis is to estimate total stress by summing acting elastic stress levels excluding residual stress to get:

$$\sigma/E = e \tag{6.2}$$

Next e/e_y is calculated. This value is used to enter Figure 6-3 to determine a value of ϕ. If the structure is in the as-welded condition, the axis which includes correction for residual stresses should be used. A correction of $\phi = .4$ is used to account for the effect of residual stress, i.e.,

$$\phi_{\text{as welded}} = \phi_{\text{stress relieved}} + .4 \tag{6.3}$$

With the value of ϕ determined the maximum allowable flaw size is calculated from:

$$a_{cr} = \frac{1}{\phi 2\pi} \quad \frac{\delta_c}{e_y} \tag{6.4}$$

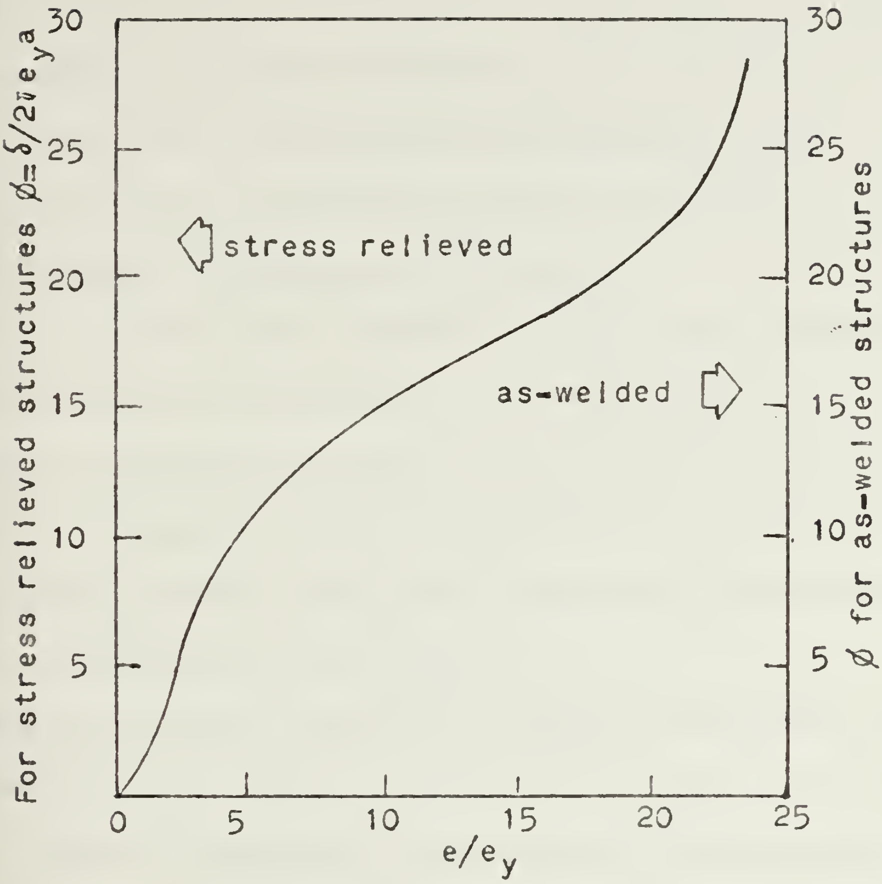


FIGURE 6-3. ϕ against e/e_y.

The successful application of these and other analysis techniques, employing fracture mechanics concepts, to practical, real world problems, has been demonstrated and results presented in the literature.[64,53,69,66,68,71,67,52,70] Fracture mechanics techniques have found particular applicability in the analysis of pressure vessels.

6.4 Application to Acceptance Standards

It is becoming more widely accepted that fracture mechanics concepts can provide the most rational basis for weld defect acceptance standards. This approach directs attention to assessing the significance of weld defects and providing new criteria for defect rejection based on the "fitness for purpose" philosophy.

While the present impact of fracture mechanics technology on weld defect acceptance standards and codes is not overwhelming, there is encouraging evidence that an attempt is being made, at some levels, to incorporate the fracture mechanics concepts into future versions of weld defect acceptance standards.

In the area of national and international standards, the use of fracture mechanics is just beginning. There has been, however, some cases where these concepts have been employed to establish requirements for a particular industry or customer. An example of this is the United Kingdom Turbine Makers. This group adopted defect acceptance standards, based on fracture mechanics analysis, for their rotor forgings.[71]

Current developments in the standrads area include a draft modification to Section III and XI of the ASME Pressure Vessel Code related to the evaluation of flaw indications;[71] a draft modification to the British Standard Rule for the derivation of acceptance levels for defects in welded joints;[71] and a proposed acceptance standard drafted by the International Institute of Welding Commission X - Working Group on Significance of Defects.[28] As a result of this activity, acceptance standards are being proposed which consciously permit, for the first time, a structure to be in service even though it may contain a crack or crack-like defect.

All three proposals introduce the concept of Engineering Critical Assessment (ECA). The first step employed in applying ECA is to define the stresses. Three categories of stresses are considered.

1. Principal stresses such as membrane and bending stress.
2. Secondary stresses such as residual and thermal stress.
3. Peak stresses at stress concentrations.

The established stress level is then fed into the appropriate fracture mechanics model along with the material properties (K_{1c} or δ_c) to obtain a value for the maximum allowable defect size ($\bar{a}_{cr}$).

In the British Standard Rule and IIW proposals, the various stress levels are accounted for by varying the constant in the fracture mechanics assessment equation.

Whenever the fracture toughness value is not available or is not directly measured, the various drafts provide correlation data with Charpy V, Dynamic Tear Test, or NDT for specific materials.

With the critical crack size determined, the next step is to relate the size of the actual crack, which may have varying shape and configuration, to the critical crack size. The British Standard Rule and IIW proposals make use of a most critical dimension ($\bar{a}$) which is defined in different ways for different defects. The definition of $\bar{a}$ follows the same lines as that proposed by Burdekin.(69) For a crack more than .7 of the thickness, the critical dimension is length. For a less deep crack, it is depth. Provision is also made to include interaction between defects which are close together. Defects near a hole, nozzle, or at a fillet weld are also dealt with. The ASME proposal employs the concept that the actual defect should be completely circumscribed by an elliptical or circular planer area of appropriate size.

The basis for acceptability is a comparison of the defect parameter $\bar{a}$ with the maximum allowable flaw size, $\bar{a}_{cr}$. If $\bar{a}$ is less than $\bar{a}_{cr}$ then the flaw is acceptable. If $\bar{a}$ is greater than or equal to $\bar{a}_{cr}$ the flaw is unacceptable.

Each of the proposals have additionally built in to the fracture assessment an analysis of crack growth due to fatigue. Items which are not taken into consideration in the

proposals include crack growth due to corrosion, stress corrosion, corrosion fatigue and creep.

The IIW proposal also makes provision to handle non-planer defects such as porosity and solid inclusions.

Each proposal attempts to reduce large amounts of fracture mechanics data and results into terms that can be easily employed by the engineer. Each draft represents a major contribution to the development of weld defect acceptance standards based upon fracture mechanics concepts. The implementation of proposals such as these would lead to cheaper and more reliable welded structures.

To give a specific example of acceptance standards which were developed using fracture mechanics analysis, the data in Table 6-2[64,17] is presented. These standards were proposed for specific application to the flaw assessment in boiler drum/nozzle welds.

Before concluding this discussion on weld defect acceptance standards, a distinction between acceptance based on quality control, and acceptance based on fitness for purpose should be made.

If the existing codes were totally discarded in favor of a standard based on fitness for purpose, an undesirable drop in weld quality would probably ensue. On the other hand, it has been demonstrated that continued reliance on existing standards is not the answer either. Perhaps the best approach would be to adopt a dual standard. Quality control standards would be applied at a level consistant with the

TABLE 6-2. General specification of permissible defect size

Defect	Defect Size (2a), mm			
	Before Stress Relief		After Stress Relief	
	Elongated, a << b	Penny-shaped, a = b	Elongated, a << b	Penny-shaped, a = b
Embedded isolated defects	14	32	30	47
Defects within 2a of the surface	7	16	15	23

Multiple defects less than 4a from each other should be considered as a combined defect whose boundary encloses the individual defects.

quality of weld that a competent welder can reasonable be expected to achieve. Defects at, or less severe, than given in such a quality control standard would be acceptable. If more severe defects were found, rejection would not be automatic. Additional evaluation of the defect would be carried out based upon the fitness for purpose concept. Acceptance standards utilizing fracture mechanics analysis such as the Engineering Critical Assessment would be employed for this evaluation. It should also be noted that rejection and/or repair decisions might be influenced by previously documented experience with similar material, stresses and environmental combinations.

Through such an approach, good welding practice would be maintained and unnecessary repair welding would be eliminated.

Perhaps one day, experience combined with the fracture mechanics approach with input from fabricators, inspectors, and consumers, as well as technical societies and regulatory agencies, will lead to the development of improved weld defect acceptance standards.

PART II

SYSTEMS APPROACH TO BRITTLE FRACTURE PREVENTION AND ITS APPLICATION

CHAPTER 7

FULL FRACTURE MECHANICS ANALYSIS FOR BRITTLE FRACTURE PREVENTION

7.1 General

In order to achieve immunity from brittle fracture, a full fracture mechanics analysis should be systematically applied to the structure. This includes analysis starting at the design stage and carried on through to the operational stage.

A flow chart describing the systems approach to brittle fracture prevention is given in Figure 7-1. In the design stage, the analysis begins with the material selection, the determination of structure geometry and stress state, and a consideration of NDT methods for weld inspection. A failure analysis is then carried out to see if the material properties, NDT method, and stress state are sufficiently compatible to provide the desired immunity from brittle fracture. As shown in the chart, if the compatibility is not achieved, the designer must make trade-offs between selecting new materials, lowering the design stresses or specifying improved NDT techniques which allow for smaller flaw detection.

The trade-offs continue until a suitable design is obtained. The structure then passes into the construction phase. Here, the material obtained from industry is inspected to ensure that it meets the specified properties.

If it does not, it is rejected. Material which meets the specifications is fed into the construction area where the various parts are cut and welded together to form the final structure. During the welding process, weld quality control standards are applied. Detected weld defects that surpass the quality control standards are further assessed based upon a 'fitness for purpose' philosophy. Weld defect acceptance standards derived from fracture mechanics concepts are employed for this purpose. Acceptable flaws are allowed to remain in the weld. Flaws found to be unacceptable are marked for removal and repair welding.

When the structure is placed in service, it will not be defect free. The weld defects which were allowed to remain were assessed as acceptable for a given set of conditions. If changes in the specified operating conditions are experienced, the acceptability of the existing flaws may be invalidated. It is therefore necessary to monitor and control the in-service environment, loading, and material characteristics to ensure these conditions are maintained.

NDT is also performed while the structure is in service to verify the continued acceptability of the existing weld defects during the life of the structure, and to detect any new defects which may develop.

In the paragraphs that follow, the design and construction phases will be discussed in more detail. Specific examples will be given showing the kind of analysis that can

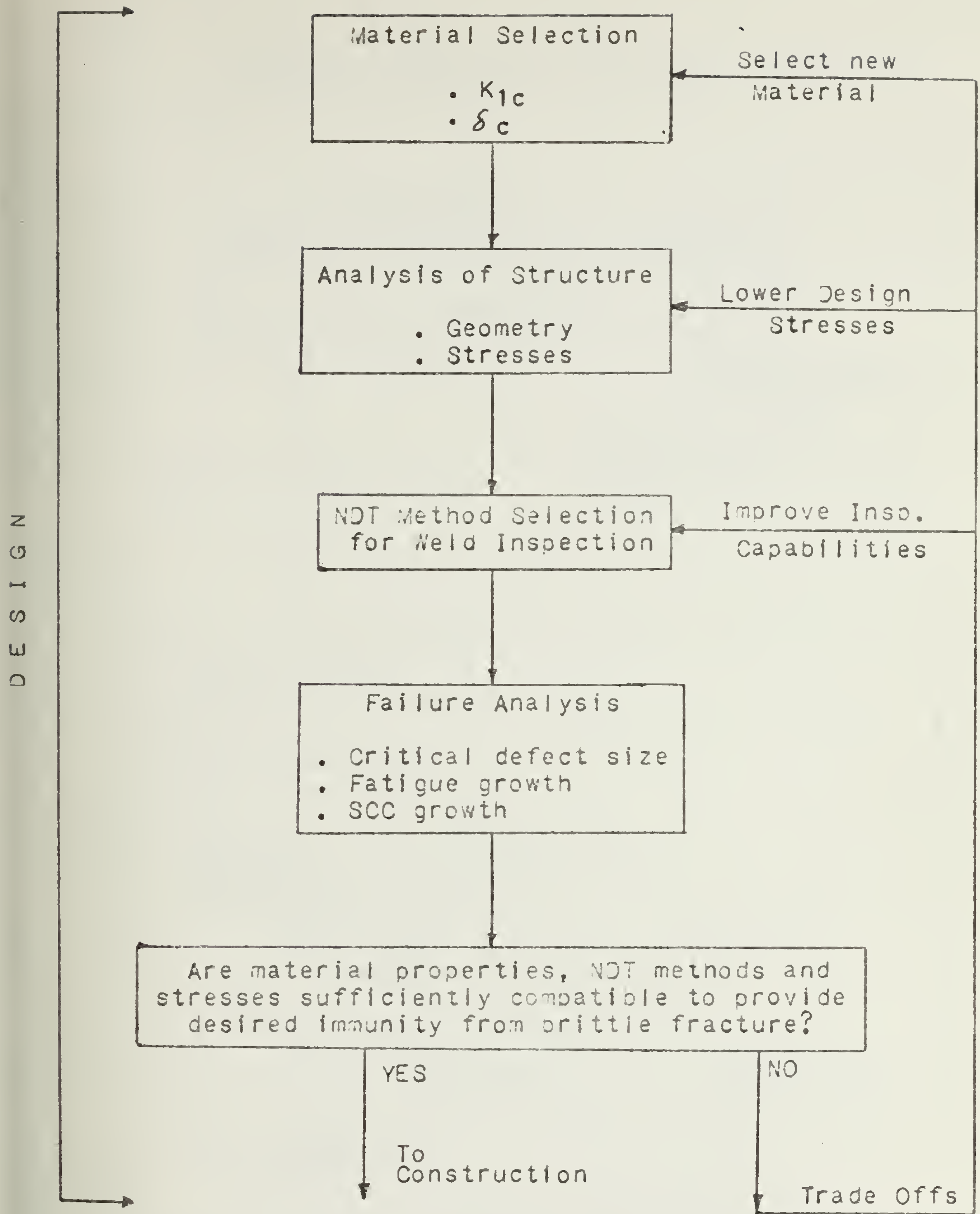


FIGURE 7-1. Full Fracture Mechanics Analysis for Brittle Fracture Prevention.

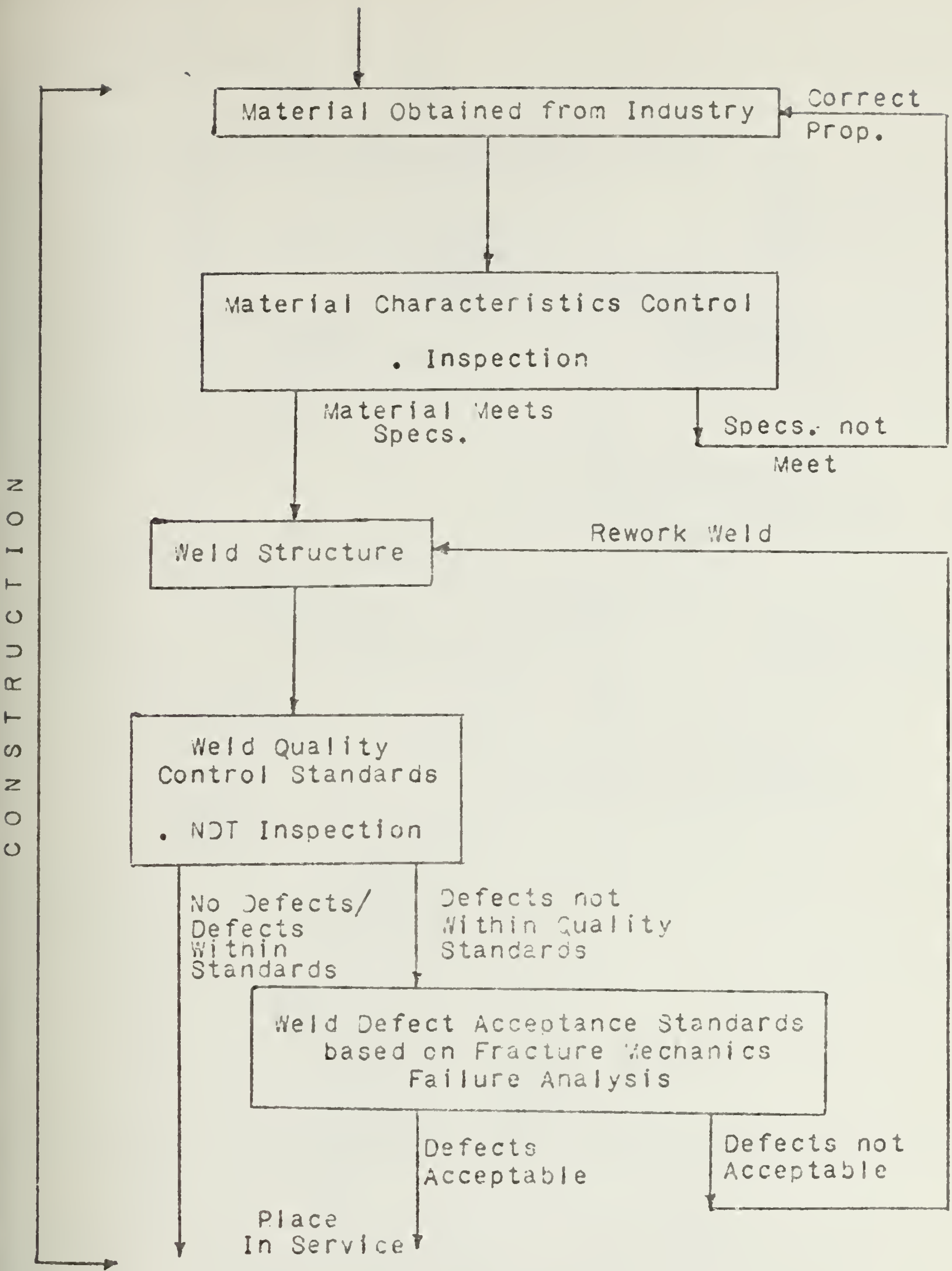


FIGURE 7-1(cont.). Full Fracture Mechanics Analysis for Brittle Fracture Prevention.

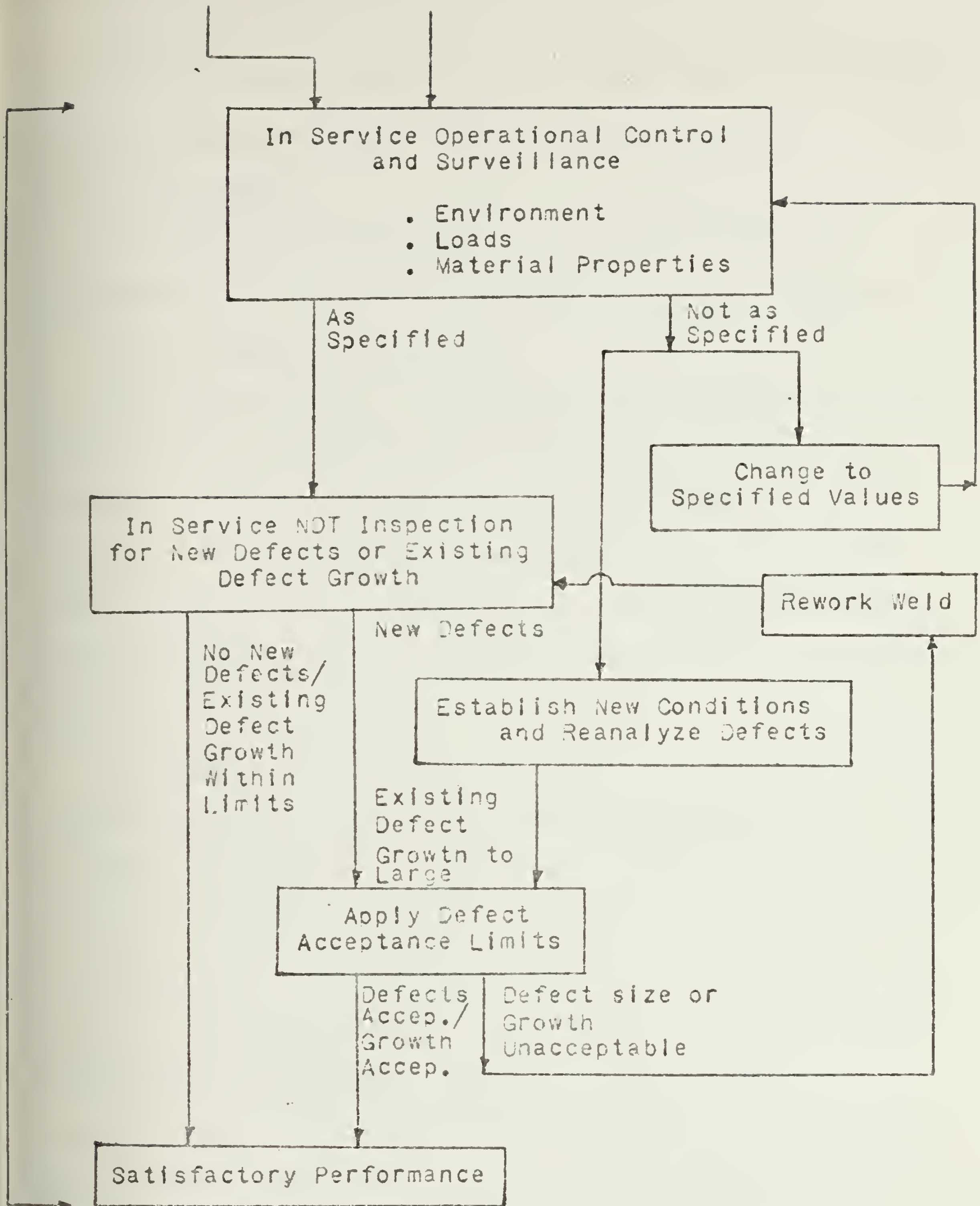


FIGURE 7-1 (cont.). Full Fracture Mechanics Analysis for Brittle Fracture Prevention.

be undertaken during these phases. The numerical examples are based upon a nuclear reactor pressure vessel.

7.2 Design Phase

The design phase encompasses material selection, structural analysis, NDT selection, and failure analysis.

7.2.1 Material Selection

In the selection of a material for a structure, conventional mechanical properties such as yeild strength, ultimate strength, impact value, total elongation, and reduction in area must be considered in the light of the requirements of the structure. In nuclear reactor pressure vessel applications, the neutron embrittlement characteristics of the material must also be considered.

In addition to these properties, the fracture toughness can be employed as a basis for comparing the relative merits of different materials. Toughness of either the linear elastic or COD type can be used. As noted in Chapter 4, this comparison must be made using the parameters $(K_{1c}/\sigma_y)^2$ or (δ_c/e_y). Toughness testing will determine whether the toughness of one material is better than another in the parent state. It can also show if fabrication and welding can cause any appreciable deterioration in toughness. Toughness tests can be of help in determining the optimum heat treatment, for a given fabrication procedure, in light of fracture toughness considerations.

If the material is selected with sufficient toughness in the welded condition to prevent initiation of brittle fracture, then a high standard of non-destructive examination may prove unnecessary later on.

7.2.2 Analysis of the Structure

After the material has been selected, the actual design of the structure can be carried out. Here, the geometry of the structure is defined and the design stresses determined. During the structural design process, certain steps can be taken to further ensure against failure by brittle fracture. For instance, if certain weld regions are known to have reduced toughness, steps can be taken to make sure these regions are not placed in areas of stress concentrations. Also, the ease with which such regions can be inspected for weld defects can be an input to the final design. The specified welding process and the need for heat treatment and their impact on the structure must also be seriously considered at the design stage.

Stress analysis procedures have been briefly discussed in Part I. In certain structures, such as nuclear reactor pressure vessels, the stress analysis is usually carried out by a computer. This can be accomplished through the solution of a linear system of equations or, for very complex geometries, by finite element methods.

7.2.3 NDT Method Selection

The importance of NDT has been repeatedly emphasized throughout this paper. During the design stage, decisions are made as to what NDT method, or methods, can best serve the inspection requirements. Accuracy of the NDT method, its detection capability, availability of equipment, ease of inspection, and expense must all be considered. As the design evolves, the need for inspection must be kept in mind and made as easy as possible. The detection capabilities of the NDT method will require evaluation based upon the allowable defect size determined in later analysis. Obviously, the NDT technique must be capable of detecting flaws which are smaller than the allowable defect size.

7.2.4 Failure Analysis

The step-by-step procedure in assessing the significance of cracks or crack-like defects using fracture mechanics concepts has been outlined in Chapter 6. The object of such an analysis is to determine the crack size that will result in the catastrophic failure of the structure. Allowance for fatigue crack growth and environment induced crack growth must also be included when applicable.

The outcome of the failure analysis will determine if the selected material properties, NDT method, and design stresses are compatible. The degree of compatibility will set the limit on immunity from brittle fracture.

A numerical example follows which demonstrates the application of fracture mechanics analysis during the design phase. The example deals with a nuclear reactor pressure vessel. It was assumed that the most severe weld defect that could be experienced by the pressure vessel was a semi-elliptical surface crack oriented normal to the hoop stress. For this case, the stress intensity factor is given by:

$$K_1 = \sigma\sqrt{\frac{1.21\pi a}{Q}} \tag{7.1}$$

where

K_1 = stress intensity factor

Q = flaw shape parameter

a = crack depth

σ = hoop stress

The value of Q for various crack configurations can be obtained from Figure 7-2.[66]

The failure conditions are established by rearranging equation (7.1).

$$a_{cr} = \frac{{K_{1c}}^2 Q}{1.21\pi\sigma^2} \tag{7.2}$$

The analysis was carried out using two steel types (A533, Grade B, Class I and HY-130) and for two different flaw configurations.

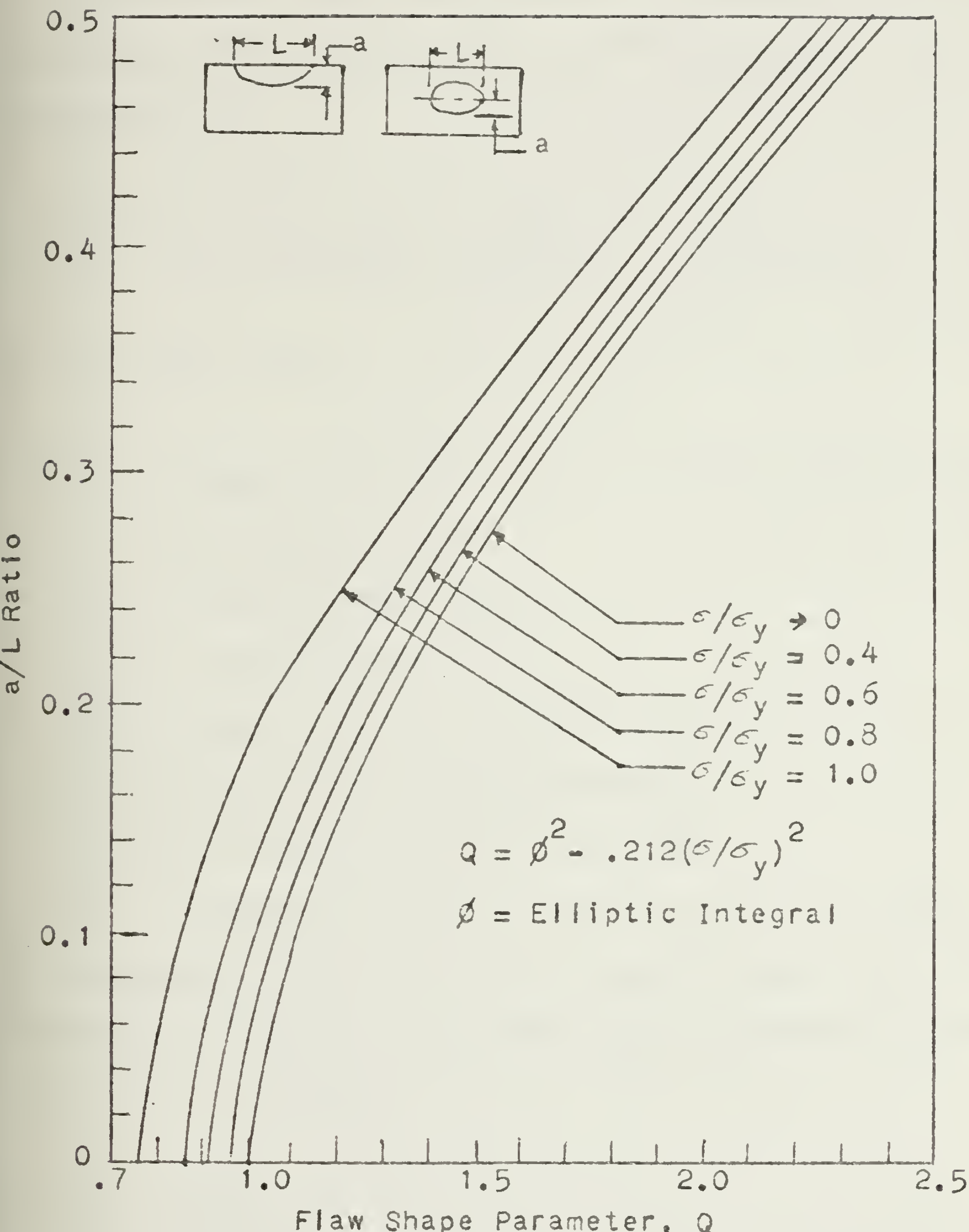


FIGURE 7-2. Flaw shape parameter curves for surface and internal cracks.

Since the reactor pressure vessel undergoes cyclic loading, the crack growth resulting from such loading must be investigated. For this purpose, a general cyclic life expression given by Wessel et. al.[66] was used. The expression is:

$$N = \frac{2}{(m-2)C\,M^{m/2}\Delta\sigma^{m}}\left[\frac{1}{a_i^{(m-2)/2}} - \frac{1}{a_{cr}^{(m-2)/2}}\right] \tag{7.3}$$

for $m \neq 2$ and where

N = number of cycles for an initial crack to grow to critical size

a_i = initial crack depth

a_{cr} = critical crack size

m = slope of the log da/dN versus log Δ K curve

C = empirical intercept constant

$\Delta\sigma$ = the applied cyclic load range

M = component geometry and flaw shape parameter

The expression of equation (7.3) applies where the relationship between applied load, flaw size, and stress intensity factor is of the form:

$$K_1 = \sigma\sqrt{Ma} \tag{7.4}$$

It is assumed that $\Delta\sigma$ remains constant throughout the life of the vessel and the mean stress does not influence the

results. The value of the component geometry and flaw shape parameter (M) can be found by comparing equation (7.4) with equation (7.1). Thus

$$M = 1.21\ \pi/Q \tag{7.5}$$

With $\Delta\sigma$, m, C, and a_{cr} known, values of initial crack size (a_i) can be assumed and, through the use of equation (7.3), a value for N can be obtained. By using a simple computer program, outlined in Figure 7-3, values of N can be determined for a wide range of assumed initial crack sizes.

This calculation was made for the material, crack configuration and stress range combinations shown in Table 7-1. The results are shown in Figures 7-4 to 7-7.

The stress ranges selected were based upon cycling from zero to the A.S.M.E. code maximum allowable stress of 26,700 psi and for cycling from zero to 40,000 psi (a safety factor of 1.5).

The data represented in Figures 7-4 to 7-7 provides the necessary information upon which compatibility judgements can be made. By using these figures, the cyclic life of the pressure vessel can be predicted for a desired stress range and for any initial crack size up to the critical crack size. This cyclic life and initial defect size can then be compared with the desired cyclic life of the vessel and the inspection capabilities of the selected NDT method.

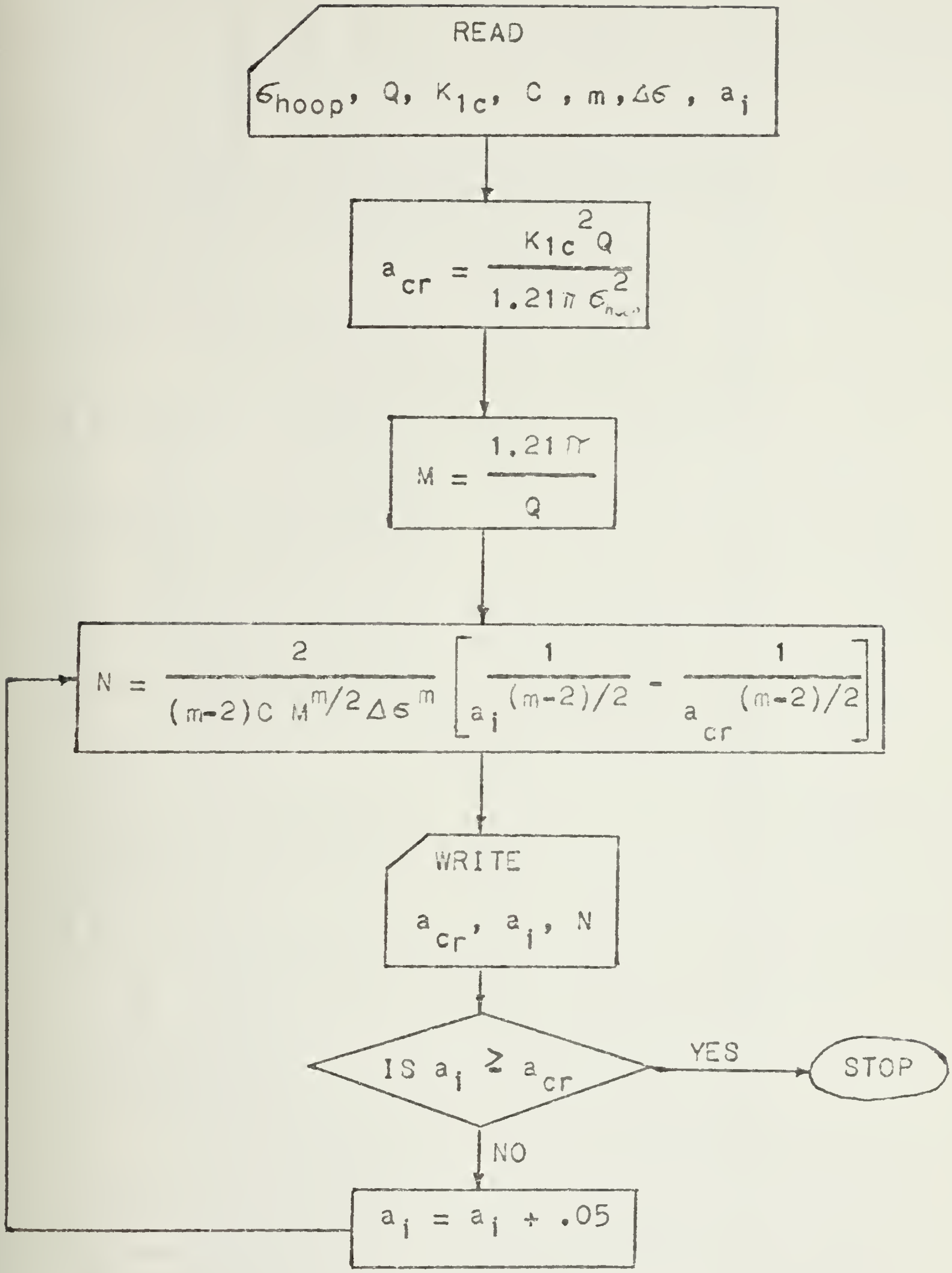


FIGURE 7-3. Computer program to calculate cyclic life given an initial crack size.

TABLE 7-1. Analysis Conditions

MATERIAL	σ_y	σ_{hoop}	Crack Conf. a/L	Q	K_{1c} Weld Metal	C	m	$\Delta\sigma$	Fig.
Unirradiated	50 ksi	45 ksi	.1	.903	180 ksi-in$^{\frac{1}{2}}$	1×10^{-15} *	2.2	26,700psi	7-4
A533	50 ksi	45 ksi	.1	.903	180 ksi-in$^{\frac{1}{2}}$	1×10^{-15}	2.2	40,000psi	7-4
Grade B Class I	50 ksi	45 ksi	.2	1.14	180 ksi-in$^{\frac{1}{2}}$	1×10^{-15}	2.2	26,700psi	7-5
Steel	50 ksi	45 ksi	.2	1.14	180 ksi-in$^{\frac{1}{2}}$	1×10^{-15}	2.2	40,000psi	7-5
Unirradiated	130 ksi	50 ksi	.1	1.06	110 ksi-in$^{\frac{1}{2}}$	$.771\times10^{-11}$ @	4.0	26,700psi	7-6
HY-130	130 ksi	50 ksi	.1	1.06	110 ksi-in$^{\frac{1}{2}}$	$.771\times10^{-11}$	4.0	40,000psi	7-6
Steel	130 ksi	50 ksi	.2	1.27	110 ksi-in$^{\frac{1}{2}}$	$.771\times10^{-11}$	4.0	26,700psi	7-7
	130 ksi	50 ksi	.2	1.27	110 ksi-in$^{\frac{1}{2}}$	$.771\times10^{-11}$	4.0	40,000psi	7-7

* for ΔK in psi-in$^{\frac{1}{2}}$

@ for ΔK in ksi-in$^{\frac{1}{2}}$

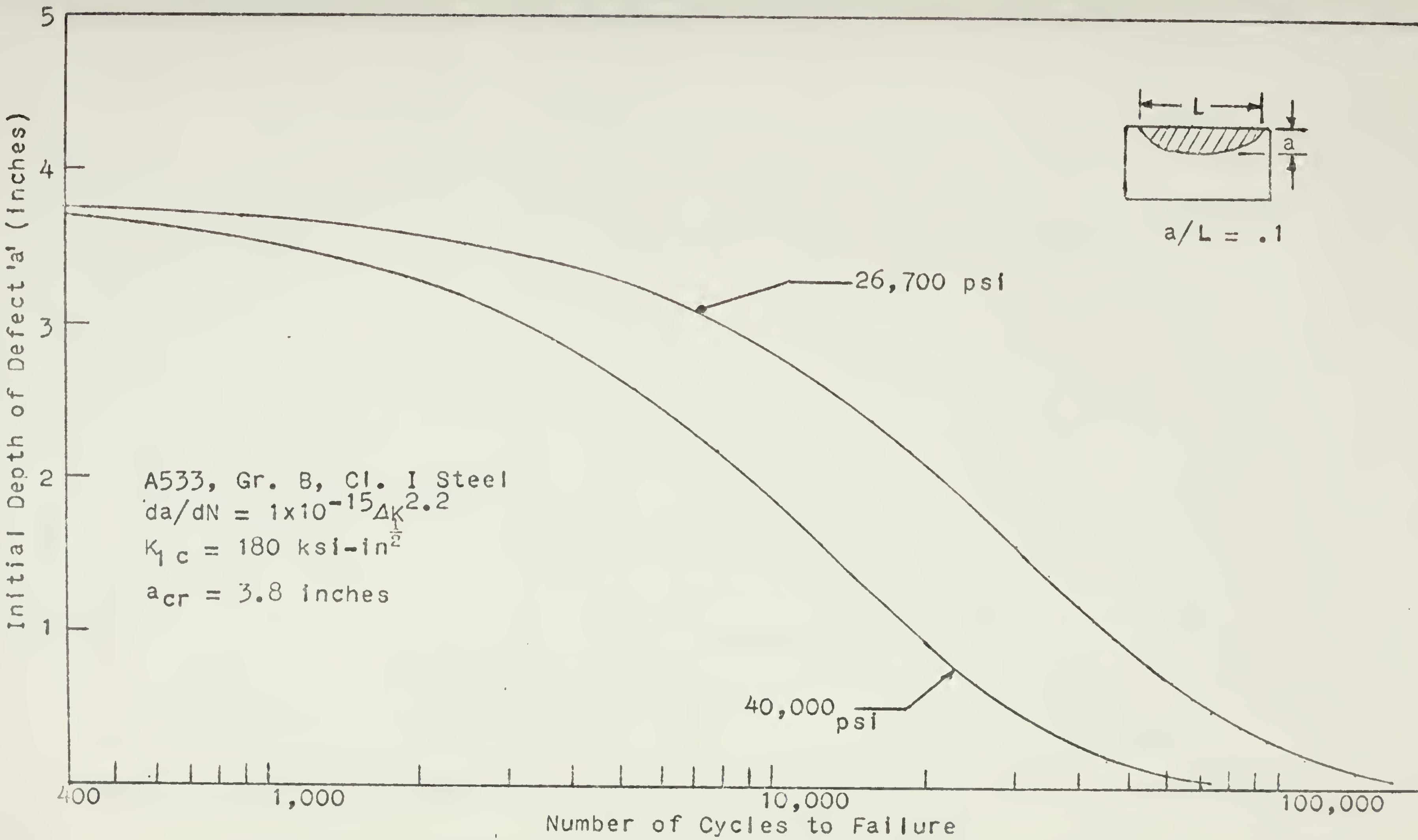


FIGURE 7-4. Cyclic life of A533 steel for various initial defect depths and cyclic stress levels.

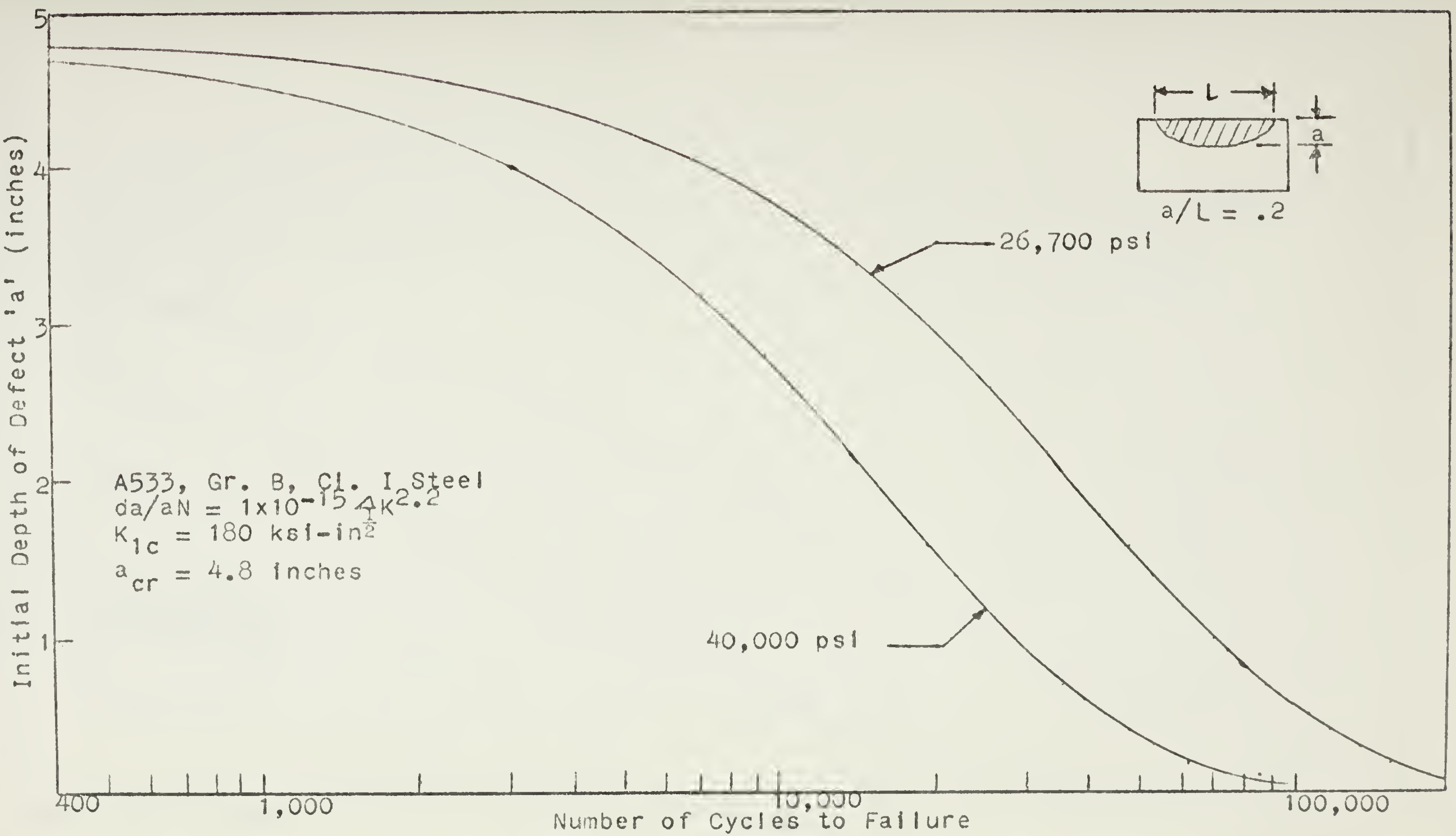


FIGURE 7-5. Cyclic life of A533 Steel for various initial defect depths and cyclic stress levels.

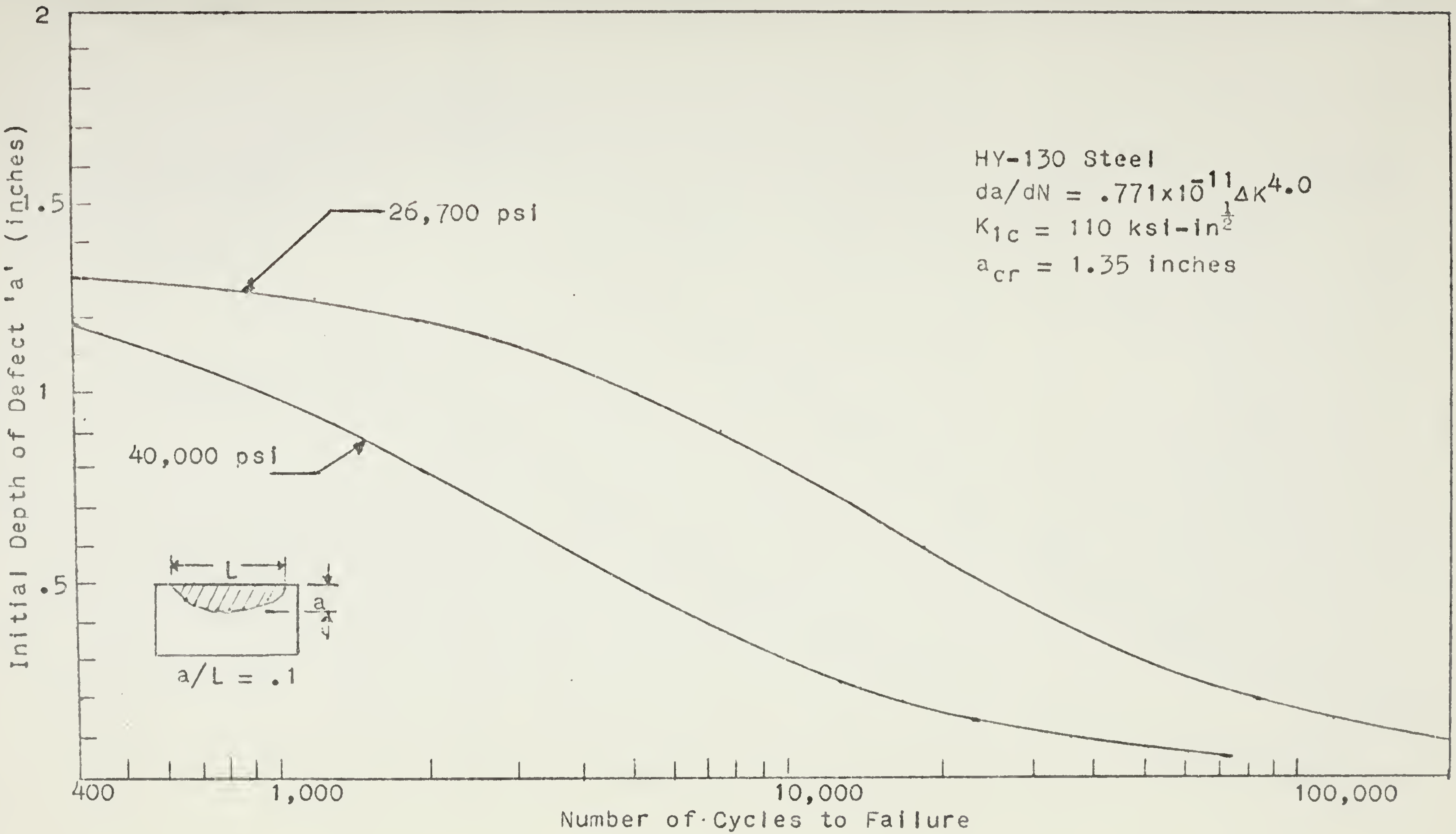


FIGURE 7-6. Cyclic life of HY-130 steel for various initial defect depths and cyclic stress levels.

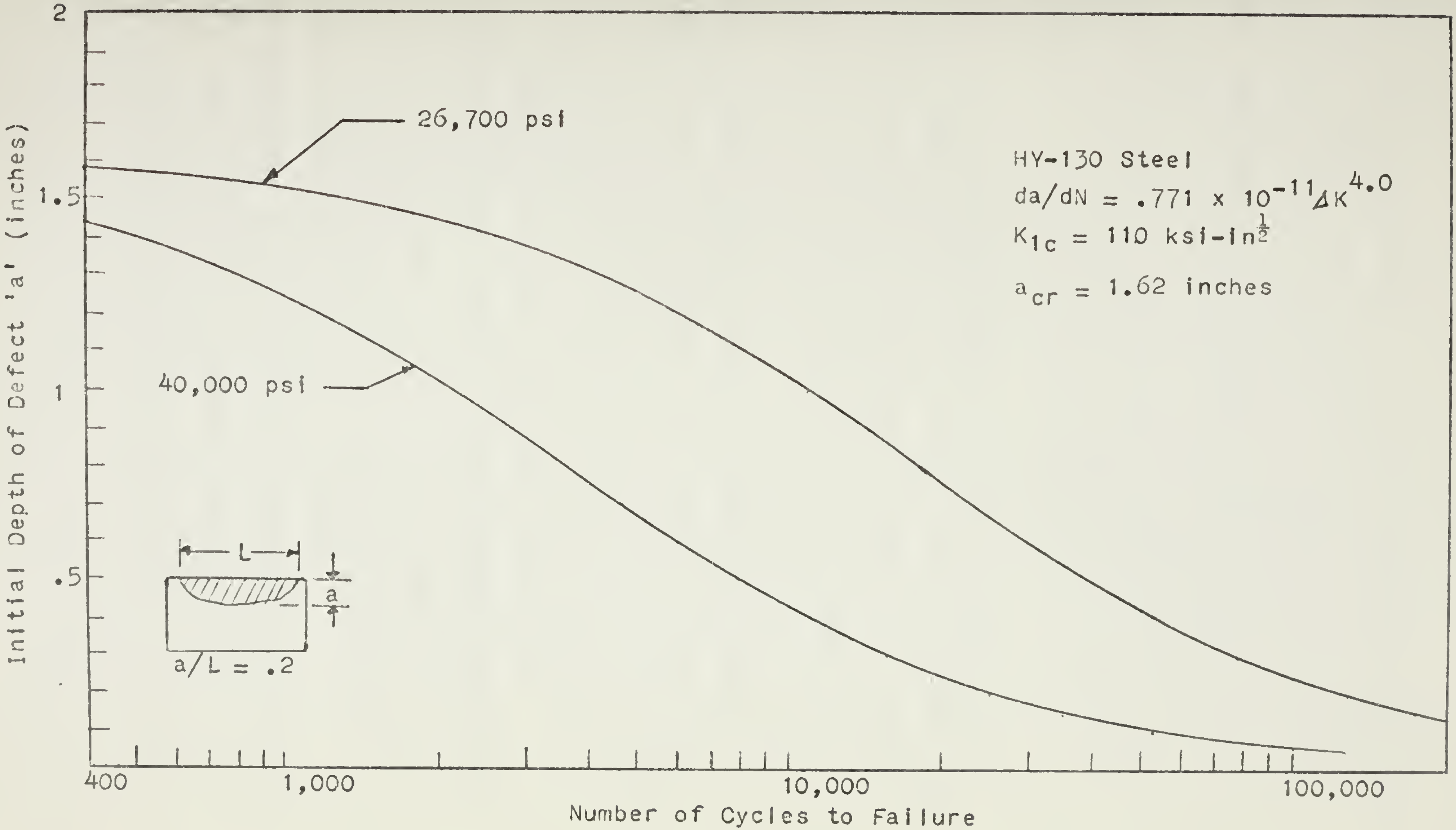


FIGURE 7-7. Cyclic life of HY-130 steel for various initial defect depths and cyclic stress levels.

To illustrate this, assume that the nuclear reactor pressure vessel experiences 10,000 full pressure cycles from zero to the maximum pressure during its lifetime. Furthermore, the selected NDT method has a capability of detecting surface flaws whose size is greater than .5 inches deep. The cyclic life of a vessel with an initial weld defect of .5 inch depth (set by the NDT detection capability) for the various parameter combinations of Table 7-1 is shown in Table 7-2.

From results such as these, real significance can be applied to safety factors. The safety factor on vessel life for the various cases is also given in Table 7-2. We see that with the A533 steel, the safety factor ranged from a low of 4.33 to a high of 10.54. The higher stress range resulted in lower safety factors, as would be expected. With the HY-130 steel, however, only the low stress range cases provided a factor of safety on the life of the vessel. Clearly some reevaluation of design decisions would be in order for the HY-130 steel, high stress range case.

In each instance, the A533 steel performed much better than did the HY-130 steel. This is as it should be, since the HY-130 steel is not nearly as tough (with $(K_{1c}/\sigma_y)^2 = .72$) as the A533 steel (with $(K_{1c}/\sigma_y)^2 = 12.96$).

An evaluation of the ability of the selected NDT method to detect flaws below the allowable size is made as follows. Assume a nuclear reactor pressure vessel made of the A533

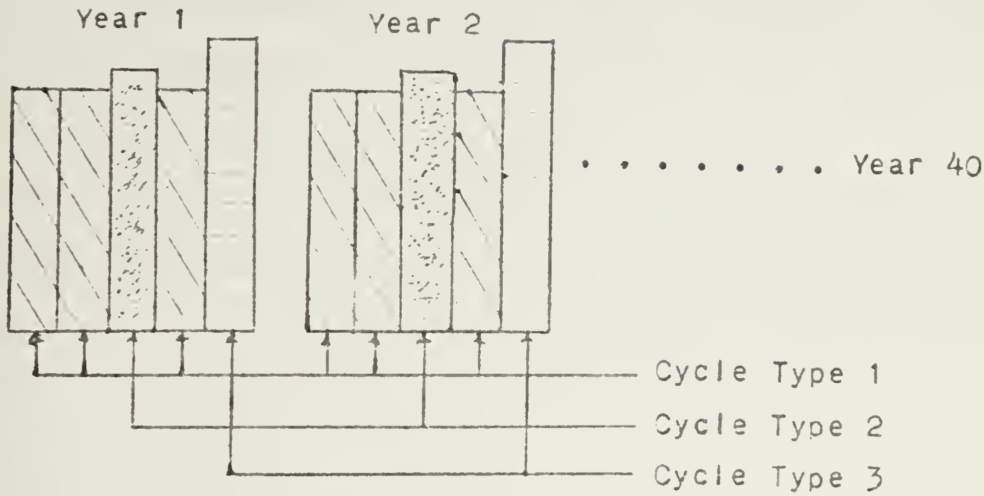
TABLE 7-2. Cyclic Life for Nuclear Reactor Pressure Vessel

MATERIAL	LOAD RANGE (psi)	CRACK CONF. a/L	INITIAL WELD DEFECT (in)	CYCLIC LIFE (cycles)	SAFETY FACTOR ON LIFE
A533	26,700	.1	.5	74,000	7.4
	26,700	.2	.5	105,400	10.54
	40,000	.1	.5	30,400	3.04
	40,000	.2	.5	43,300	4.33
HY-130	26,700	.1	.5	25,000	2.5
	26,700	.2	.5	39,000	3.94
	40,000	.1	.5	4,900	--
	40,000	.2	.5	7,800	--

steel with a/L = .1, desired safety factor on cyclic life of 10, and a stress range of 26,700 psi. Thus for 100,000 cycles at 26,700 psi, we obtain, from Figure 7-4, an initial crack size of .25 inches. This represents the maximum allowable weld crack size that the vessel can have and still meet its service requirements. Since the selected NDT method cannot detect flaws smaller than .5 inches deep, a need exists to specify a different NDT method or, to change the material or stress range in order to bring the flaw size within detection capabilities. An alternative to these changes would be to accept a safety factor on cyclic life less than a value of 10.

The results presented were obtained for unirradiated steels. Before they can be used in the design, the effect of irradiation on the material must be established and accounted for.

It is also important to consider the cumulative fatigue crack growth when the reactor pressure vessel experiences different types of loading of varying numbers of cycles. To investigate this case further, a load history was assumed for the pressure vessel as shown in Figure 7-8[70] The life time of the reactor was taken as 40 years. The purpose of the analysis was to determine the amount that an initial crack would grow during the life of the vessel, when subjected to the stated loading. The calculation was carried out by obtaining a value of ΔK_1 for the initial stress range and



		Transient	$\Delta\sigma$ (ksi)
Cycle Type 1:	1	Heat-up, Cool-down	31.795
	92	Loadings and Unloadings	2.288
	10	Step changes in power	4.040
	1	Steam dump	1.430
	2	Reactor trips	1.430
Cycle Type 2:	1	Heat-up, Cool-down	31.795
	92	Loadings and Unloadings	2.288
	10	Step changes in power	4.040
	1	Steam dump	1.430
	2	Reactor Trips	1.430
	1	Loss of load-Loss of flow	7.940
Cycle Type 3:	1	Heat-up, Cool-down	31.795
	92	Loadings and Unloadings	2.288
	10	Step changes in power	4.040
	1	Steam dump	1.430
	2	Reactor trips	1.430
	1	Loss of Load-Loss of flow	7.940
	1	Loss of Power	2.500
	1	Post-operational hydro	2.350

FIGURE 7-8. Assumed reactor operating transients.

initial crack size. A calculation of da/dN was then made and multiplied by the number of cycles that the stress range operated. This resulted in a value for the change in crack size. This change in crack size was then added to the initial crack size and a new ΔK_1 calculated for the next stress range and new crack size. This process was repeated for each stress range over the life of the reactor vessel. The crack size at the end of 40 years could then be compared with the critical crack size to determine if a fatigue problem existed under the assumed loading.

Again, a simple computer program was developed to calculate the crack growth over the 40 year load history of the pressure vessel. The program is outlined in Figure 7-9. Results of the analysis are given in Table 7-3 for A533 steel, and in Table 7-4 for the HY-130 steel. Table 7-5 shows the complete data for the 30^{th} year of operation of a vessel made of HY-130 steel. A crack configuration of a/L = .1 was used in each case. It was also assumed that the vessel had an initial surface weld crack .5 inches in depth. In each instance, no remarkable crack growth occurred over the life of the reactor pressure vessel.

In the calculations, the effect of residual stresses in the weld were neglected. Since the residual stresses do not fluctuate, they only affect the mean stress level and not the stress range.

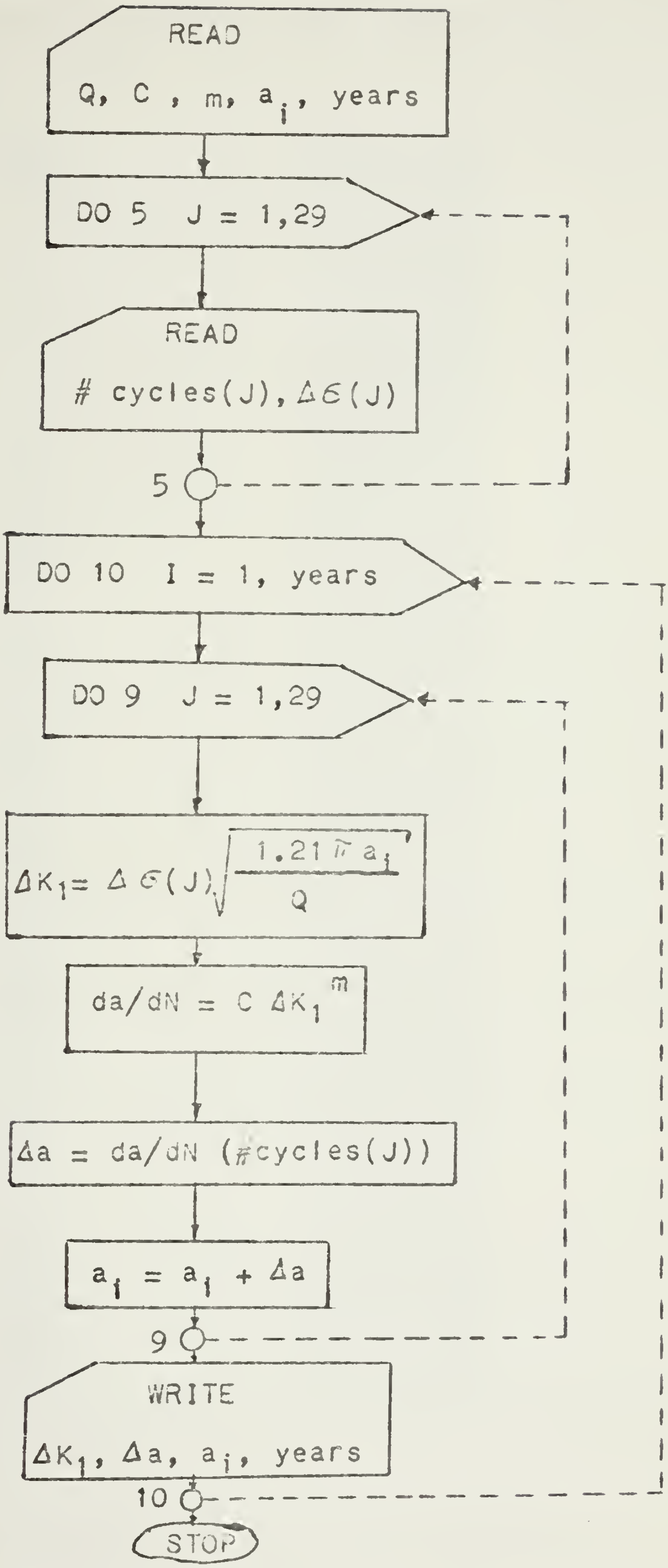


FIGURE 7-9. Computer program to calculate fatigue crack growth .

TABLE 7-3. Fatigue Crack Growth over 40 year's operation of reactor pressure vessel made of A533, Grade B, Class I steel.

YEAR	CRACK SIZE
1	0.50012779
2	0.50025558
3	0.50038338
4	0.50051123
5	0.50063932
6	0.50076741
7	0.50089550
8	0.50102359
9	0.50115168
10	0.50127977
11	0.50140786
12	0.50153595
13	0.50166404
14	0.50179213
15	0.50192022
16	0.50204849
17	0.50217688
18	0.50230527
19	0.50243366
20	0.50256205
21	0.50269043
22	0.50281882
23	0.50294721
24	0.50307560
25	0.50320399
26	0.50333238
27	0.50346076
28	0.50358945
29	0.50371814
30	0.50384688
31	0.50397563
32	0.50410438
33	0.50423312
34	0.50436187
35	0.50449061
36	0.50461942
37	0.50474846
38	0.50487751
39	0.50500673
40	0.50513619

TABLE 7-4. Fatigue Crack Growth Over 40 Year's Operation of Reactor Pressure Vessel Made of HY-130 Steel

YEAR	CRACK SIZE
1	0.50012708
2	0.50025433
3	0.50038171
4	0.50050908
5	0.50063646
6	0.50076383
7	0.50089151
8	0.50101918
9	0.50114685
10	0.50127453
11	0.50140232
12	0.50153029
13	0.50165826
14	0.50178623
15	0.50191420
16	0.50204241
17	0.50217068
18	0.50229895
19	0.50242722
20	0.50255555
21	0.50268412
22	0.50281268
23	0.50294125
24	0.50306982
25	0.50319856
26	0.50332743
27	0.50345629
28	0.50358516
29	0.50371408
30	0.50384325
31	0.50397241
32	0.50410157
33	0.50423074
34	0.50436008
35	0.50448954
36	0.50461900
37	0.50474846
38	0.50487798
39	0.50500774
40	0.50513750

TABLE 7-5. Fatigue Crack Growth for the 30th Year of Operation of a Reactor Pressure Vessel made of HY-130 Steel

CYCLE TYPE	NUMBER OF LOAD CYCLES	ΔK_1	CHANGE IN CRACK SIZE	NEW CRACK SIZE
1	1.00	42.72577	0.25692891E-04	0.50373977
	92.00	3.07467	0.63391951E-07	0.50373983
	10.00	5.42905	0.66980533E-07	0.50373989
	1.00	1.92167	0.10513981E-09	0.50373989
	2.00	1.92167	0.21027963E-09	0.50373989
1	1.00	42.72687	0.25695626E-04	0.50376558
	92.00	3.07475	0.63398204E-07	0.50376564
	10.00	5.42918	0.66987411E-07	0.50376570
	1.00	1.92172	0.10515049E-09	0.50376570
	2.00	1.92172	0.21030097E-09	0.50376570
2	1.00	42.72795	0.25698057E-04	0.50379139
	92.00	3.07482	0.63404741E-07	0.50379145
	10.00	5.42932	0.66994346E-07	0.50379151
	1.00	1.92176	0.10516106E-09	0.50379151
	2.00	1.92176	0.21032212E-09	0.50379151
	1.00	10.67050	0.99952615E-07	0.50379157
1	1.00	42.72905	0.25700792E-04	0.50381726
	92.00	3.07490	0.63411278E-07	0.50381732
	10.00	5.42946	0.67001224E-07	0.50381738
	1.00	1.92181	0.10517184E-09	0.50381738
	2.00	1.92181	0.21034369E-09	0.50381738
3	1.00	42.73013	0.25703499E-04	0.50384307
	92.00	3.07498	0.63417758E-07	0.50384313
	10.00	5.42960	0.67007932E-07	0.50384319
	1.00	1.92186	0.10518264E-09	0.50384319
	2.00	1.92186	0.21036528E-09	0.50384319
	1.00	10.67105	0.99972794E-07	0.50384325
	1.00	3.35990	0.98256026E-09	0.50384325
	1.00	3.15831	0.76713236E-09	0.50384325

The cumulative crack growth analysis presented above is also very useful in assessing the significance of a weld crack detected in the pressure vessel some time after it has been placed in service.

For nuclear reactor pressure vessels, stress corrosion cracking can be neglected. Reactor vessels are constructed with an austenitic cladding which eliminates this danger. For the purpose of comparison, however, the critical crack size for the HY-130 steel under SCC conditions was calculated. For an $a/L = .1$ and $K_{1scc} = 90$ ksi-in$^{\frac{1}{2}}$, the critical crack size was calculated to be .903 inches. This compares with $a_{cr} = 1.35$ inches for the non-SCC case. If SCC presented a significant danger to the structure, more accurate calculations should be performed as outlined in Section 5.3 of Part I.

7.3 Construction Phase

In the construction phase, the decisions and specifications arrived at during the design phase are implemented. The output is the finished structure ready to be placed in service. It is during the construction phase that the very important tasks of weld quality control and defect acceptance assessment take place.

Prior to the actual start of construction, the material to be used must be inspected to ensure that it meets the characteristics specified during the design process. If it does not, the failure analysis performed during the design phase is invalidated.

7.3.1 Weld Quality Control

As discussed in Chapter 6, even with a detailed fracture mechanics analysis of weld defects, there is still a need to maintain standards on the quality of the welding. This is best achieved by providing the welder with a set of standards that specify the quality level he is expected to maintain in his welding. Such standards are already in existance in the form of current weld defect acceptance standards. With the introduction of fracture mechanics analysis, the old standards need not be discarded but can take on the more limited role of weld quality control.

The application of the quality control standards represents the first assessment of the significance of a weld defect. If the defect meets the prescribed quality standards, no further action is required. If, on the other hand, the defect size is beyond that allowed in the standards, a further evaluation is required.

7.3.2 Weld Defect Acceptance Standards

The second evaluation of a weld defect is based on the 'fitness for purpose' philosophy. Through the application of fracture mechanics technology, flaws are assessed for their impact on the service life of the structure.

In the construction phase, real weld defects must be identified and assessed as to their significance. In accomplishing this, it is wise to make the procedures as practical and straight forward as possible. Personnel who will be making acceptance judgements may have neither the

time, nor the background, to get involved in complex procedures and concepts. This necessitates providing the man in the field with a simple means of determining the characteristics of the existing flaw, and with a firm value for the allowable crack size. Armed with these tools, he can make rapid judgements as to the acceptability of defects found in welds as the construction progresses.

The major tool of defect characterization is the NDT method employed to inspect the weld. An output of the design phase was the specification of an NDT technique capable of meeting the defect detection requirements. This NDT method can thus be relied on to detect and characterize flaws of the proper size.

Once the defect has been detected, it must be defined in a way which can be used to assess its significance. One of the broadest, yet simplest, approaches to defect definition is provided in the proposed standards of the IIW. Here, a defect parameter $\bar{a}$ is used to represent the characteristics of the actual defect. The definition is based upon an assumption that the defect can be represented as an elliptical flaw, inscribed in a rectangle constructed about the actual defect. Defects which interact are represented by an ellipse inscribed in a rectangle containing the entire group of interacting defects.

After the existing defect has been assessed in regard to dimension, interaction with other defects, and interaction with free surfaces, a single effective flaw is obtained of

length 'L' and height 'a'. Through the use of various tables and figures, the dimensions 'L' and 'a' are converted to the defect parameter $\bar{a}$. This procedure allows one to handle, in a simple way, a wide range of weld defects (not just cracks) acting individually or under very complex conditions of interaction.

In establishing the allowable defect size, simple relationships like those given in Table 6-1 can be provided for use under conditions where fatigue or environment induced crack growth are not problems. The IIW proposal provides a graphic means to determine the constant in the expressions. For structures experiencing fatigue, families of curves similar to those presented in Figures 7-4 to 7-7 can be provided for the determination of the allowable crack size.

As an example, a weld surface crack detected in a nuclear reactor pressure vessel made of A533 steel was evaluated. To perform the analysis, the following figures, as given in the IIW proposal,[28] were required.

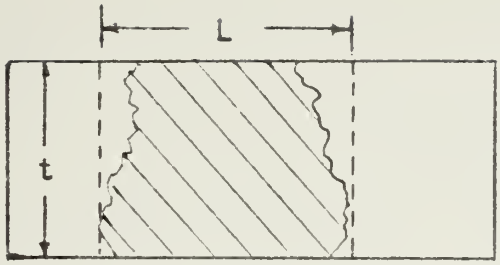
1. Figure 7-10 giving the equivalent ellipses for single defects and their effective dimensions.
2. Table 7-6, Figure 7-11 and Figure 7-12 giving the definition of the parameter $\bar{a}$.

The detected crack was defined as in Figure 7-10 (c), with L = 5 inches and a = .5 inches. The reactor pressure vessel thickness (t) was taken as a typical value of 10 inches.[70]

Entering Table 7-6 with a surface flaw having $a/t = .05 < .5$ leads one to Figure 7-12. From this figure, a value of $\bar{a} = .57$ inches was obtained.

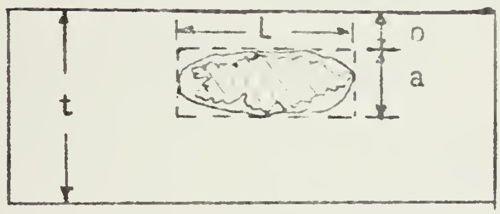
In determining the allowable crack size, the pressure vessel was assumed to have a cyclic life of 10,000 full pressure cycles ranging from zero to 26,700 psi. Using the data given in Figure 7-4, an allowable crack size for these assumed conditions of 2.8 inches was obtained. Comparing the defect parameter $\bar{a}$ with the allowable crack size clearly shows that the existing crack is well within allowable limits and can be permitted to remain in the weld.

Through the in-service monitoring of the operating conditions, and continued NDT, the applicability of these results will be ensured, and the vessel will meet its full life expectancy, immune from dangers of catastrophic failure due to brittle fracture.



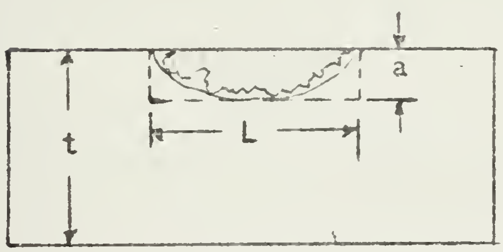
(a) Through Thickness Defect

Required Dimensions:
t, L



(b) Embedded Defect

Required Dimensions:
t, L, a, p



(c) Surface Defect

Required Dimensions:
t, a, L

FIGURE 7-10. Dimensions of Actual Defect

TABLE 7-6. Definitions of the Parameter $\bar{a}$.

Defect (or Interacted Group of Defects)	Definition of $\bar{a}$
Through thickness defect as defined by Figure 7-10 (a)	$\bar{a} = L/2$
Surface defects for which $a/t \geq 0.5$	$\bar{a} = L/2$
Surface defects for which $a/t < 0.5$	See Figure 7-12
Embedded defects for which $p/a \leq 0.5$	Use defect height a+p and treat as surface defect (Figure 7-12)
Embedded defects for which $p/a > 0.5$	See Figure 7-11

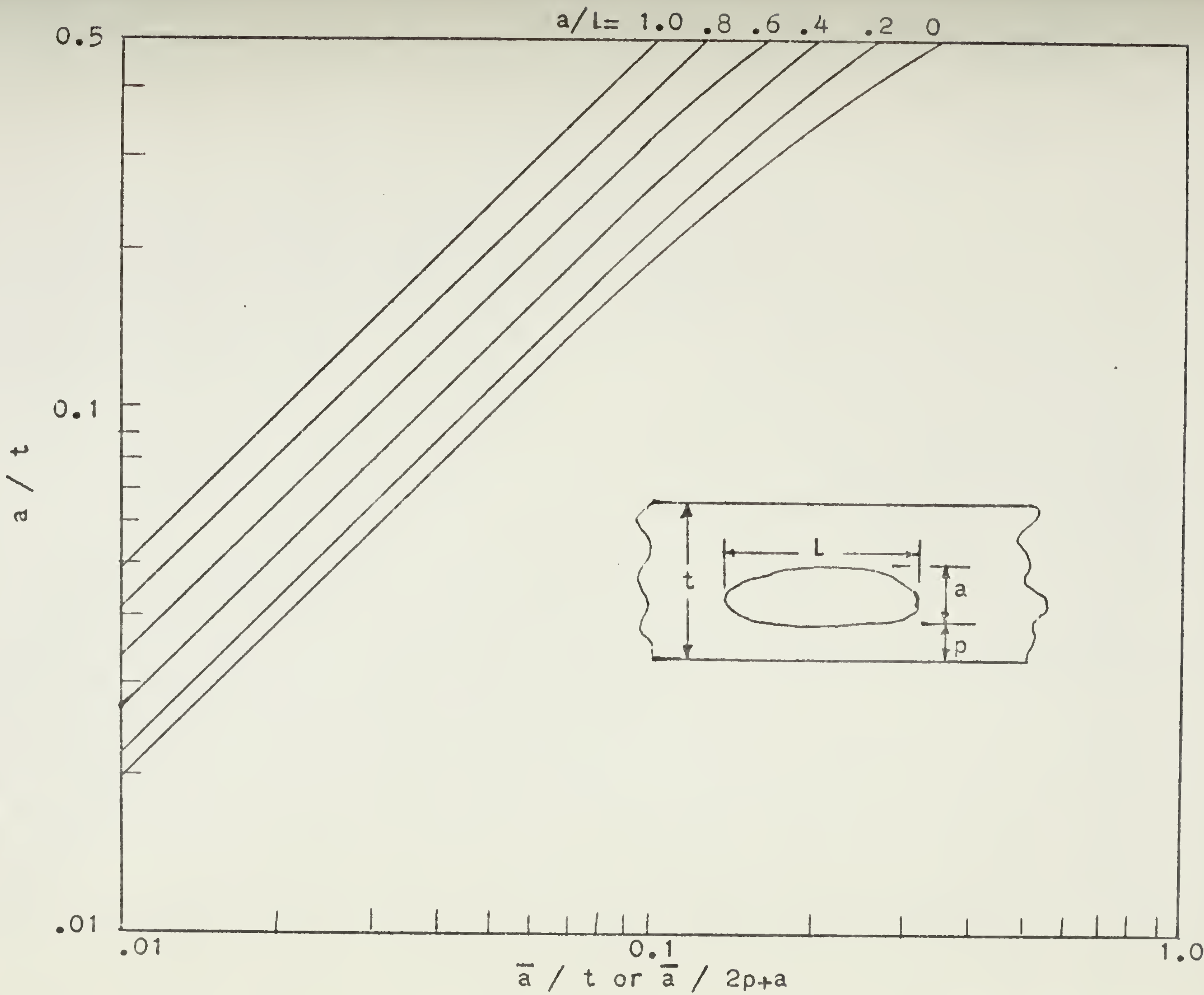


FIGURE 7-11. Relationship between actual defect dimensions and the parameter $\bar{a}$ for embedded defects.

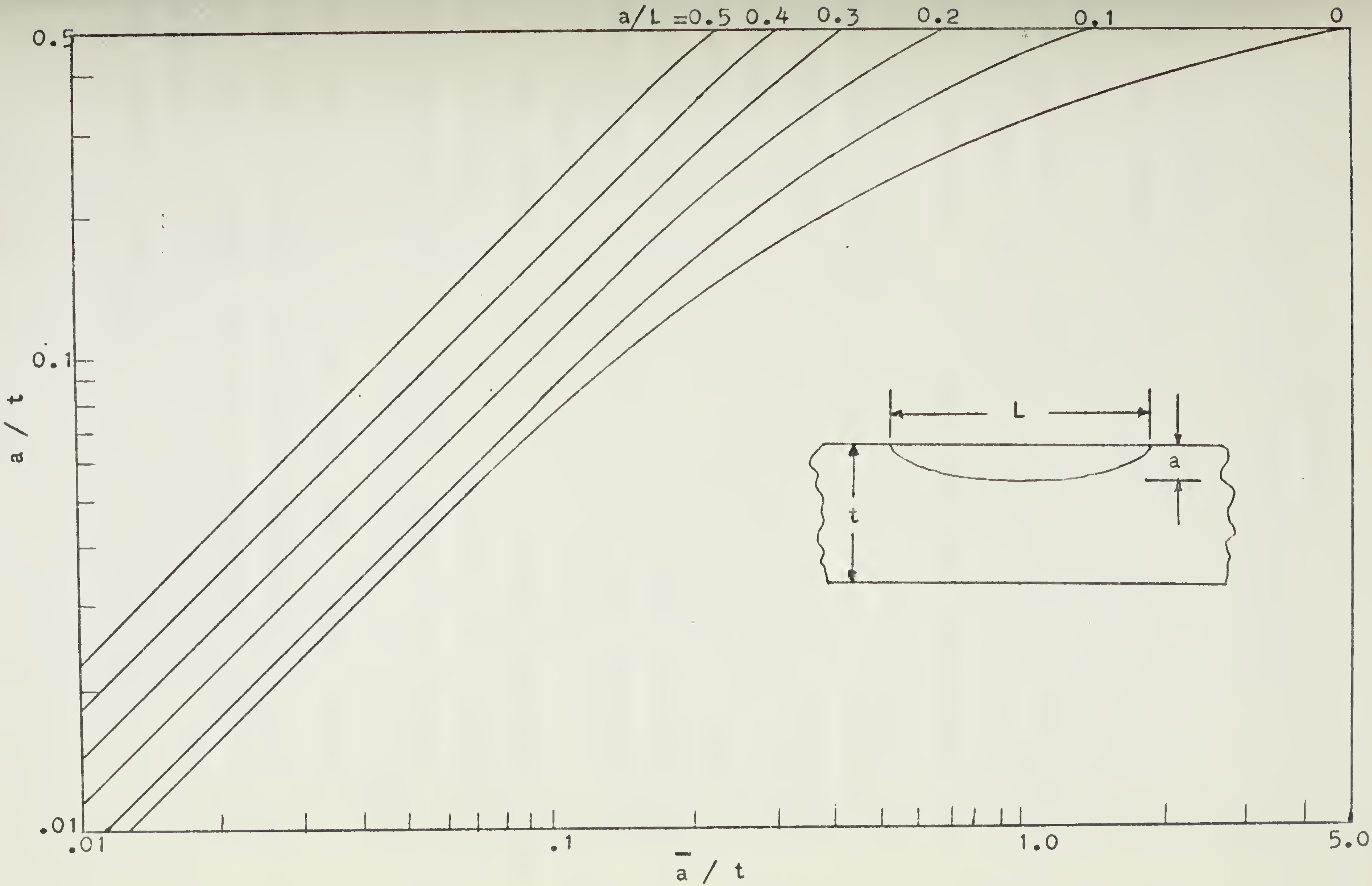


FIGURE 7-12. Relationship between actual defect dimensions and the parameter $\bar{a}$ for surface defects.

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

The foregoing chapters have discussed concepts and techniques which can provide a more rational assessment of the significance of weld defects and a means of performing a full fracture mechanics analysis for the prevention of brittle fracture. It has been shown that a need exists for assessment techniques which go beyond those represented by traditional weld defect acceptance standards, if the unnecessary waste of monetary, material and human resources resulting from structural failures and high rates of weld rework are to be reversed. A determination as to whether a defect is acceptable or not must be dependent upon standards which assess the effect of the defect on the serviceability of the structure during its expected lifetime.

The systematic application of fracture mechanics concepts to the analysis of a welded structure provides a rigorous, sophisticated, and yet, practical, means of providing a welded structure with the desired immunity from weld defect initiated brittle fracture. The linear elastic fracture mechanics techniques are the most developed and easiest to work with. However, care must be exercised in their use to ensure that the linear elastic techniques are applicable to the material in question.

When large scale yielding accompanies the brittle fracture, general yielding fracture mechanics concepts must be used. While these techniques are more complex in their mathematical formulation and the fracture toughness parameters are not as easily determined, they still provide a useful and convenient method of predicting brittle fracture initiation in welded structures under general yeilding conditions.

The importance of fatigue and environment-induced crack growth were emphasized during the study. These phenomena can result in the rapid, premature failure of a structure. Whenever fatigue or stress corrosion cracking conditions exist, they must be fully accounted for in the weld defect assessment.

In addition to providing a more rational means of assessing the significance of defects found in welds, fracture mechanics concepts can be utilized in a broad, interdisciplinary, systems-type approach to the prevention of brittle fracture. The systems-type analysis considers the interaction between material characteristics, design, fabrication, inspection and operational requirements when making a determination as to the degree of brittle fracture immunity.

In Chapter 7, it was shown that the application of fracture mechanics techniques can contribute to the overall design concept, not only in terms of permissible design stresses, but also in terms of material selection, design and location of weld details, and the choice and interpretation of non-destructive testing methods. The fracture

mechanics approach to brittle fracture prevention is also applicable during the construction phase for weld defect assessment, and during the in-service phase for on-going evaluation of existing flaws.

Clearly, the use of fracture mechanics techniques in assessing the significance of weld defects is not a cure all which will eliminate all structural failure. Employing a systems approach to brittle fracture prevention, as outlined in Chapter 7, would most certainly be costly and, for some structures, infeasible. One obvious example is the large, complex, welded structure of a naval ship. It would be quite difficult, if not impossible, to fabricate the ship allowing for various types and sizes of defects to remain, knowing that such defects would necessitate repeated testing at sea under real life conditions. In addition to the difficulties and expense in performing on-board NDT and survellience inspection, the in-service repair of weld defects, which were subsequently judged too large to remain, would prove more complicated, and thus more costly, than if they were removed during construction.

At the present level of development, the application of fracture mechanics concepts to the brittle fracture analysis of a welded structure must be approached cautiously and with full knowledge of the advantages and disadvantages. For the immediate future, the application of these concepts seems most desirable for structures for which it must be unquestionably demonstrated that the risk of brittle fracture is

minimal, or where failure would be exceptionally hazardous, expensive or embarrassing. This explains why one of the most developed applications is to pressurized equipment in the primary circuits of nuclear reactors. The use of these techniques will become even more widespread if the current trend toward larger pressure vessels, thicker sections, higher strength materials and higher stresses continues.

Another area for which this type of analysis is of help is where a failure has been detected in a particular structure, and it is necessary to define repair requirements and remedial treatment for other similar structures. For more common applications, however, it is necessary to simplify and make the analysis less expensive. Steps have been taken in this direction as represented by the draft weld defect acceptance standards discussed in Chapter 6. Here, as many stages of the analysis as possible have been incorporated in the standard specification, so that the actual steps to be taken in performing the analysis of the significance of weld defects are minimized.

8.2 Recommendations

Needless to say, there still remains a great deal of developmental and research work to be done in all areas of weld defect assessment and general brittle fracture prevention. To achieve the practical application of fracture mechanics techniques in industry, an urgent need exists for additional efforts to bring all the various fracture

mechanics factors together in a way that allows for a simple, inexpensive, full fracture mechanics analysis of a welded structure.

In the areas of fracture mechanics theory, more work is required to refine existing K solutions and to provide new ones for crack types not yet considered. The surface has just been scratched in the field of general yielding fracture mechanics. Here, the fracture toughness parameters need to be refined and research is required to develop standard procedures for estimating fracture toughness parameters for a given material through simple industrial testing.

Further development of analytical techniques is also required in the areas of fatigue and environment induced cracking.

The environmental aspects of crack growth are no doubt the most neglected and least understood. Analysis techniques which account for all the varying factors are needed along with a more rigorous means of expressing fracture toughness under stress corrosion cracking conditions. Finally, there is a need to incorporate environment-induced crack growth considerations into failure criteria used to judge the significance of weld defects.

Although further development is required, and some weaknesses exist in the analysis, it is the author's firm recommendation that all steps possible should be taken to expand the use of fracture mechanics concepts for brittle

failure analysis to encompass the design, construction, and in-service phases of a welded structure. The use of these techniques on a practical level is really just beginning. Its advancement may be met with skepticism and opposition, but the advantages that can be realized for a wide range of welded structures through more rational assessment of the significance of weld defects, are so significant that further research, development, and implementation must be encouraged wherever and whenever possible.

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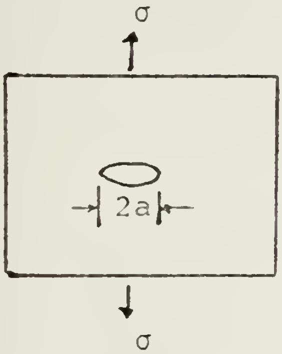
APPENDIX A

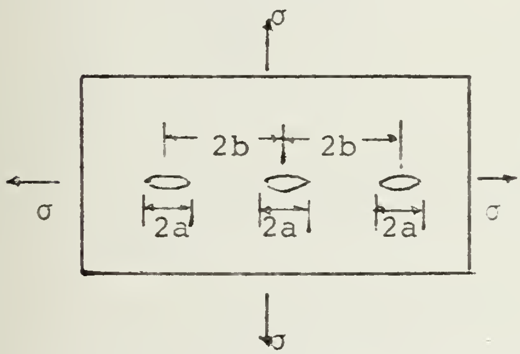
The following is a partial list of K_1 expressions for various defect shapes and loads.(36,40)

CASE 1: Infinite cracked sheet with uniform normal stress at infinity.



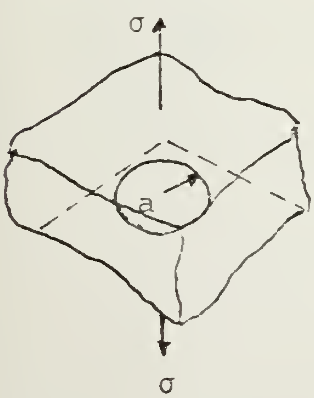
$$K_1 = \sigma\sqrt{\pi a}$$

CASE 2: Periodic array of cracks along a line in a sheet with uniform stress at infinity.



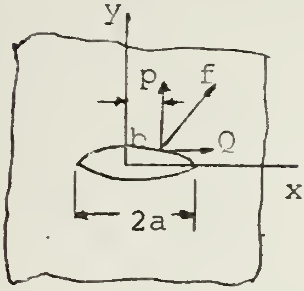
$$K_1 = \sigma\sqrt{\pi a}\ \left(\frac{2b}{\pi a}\tan\frac{\pi a}{2b}\right)^{\frac{1}{2}}$$

CASE 3: Circular disc crack in an infinite body with stress normal to plane of crack.



$$K_1 = 2\sigma\sqrt{a/\pi}$$

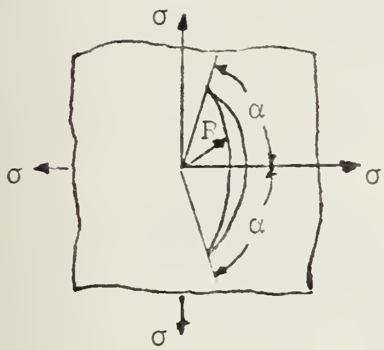
CASE 4: Concentrated force on the surface of a crack in an infinite sheet.



$$K_1 = \frac{\rho}{2\sqrt{\pi a}} \left(\frac{a+b}{a-b}\right)^{\frac{1}{2}} + \frac{Q}{2\sqrt{\pi a}} \left(\frac{\lambda-1}{\lambda+1}\right)$$

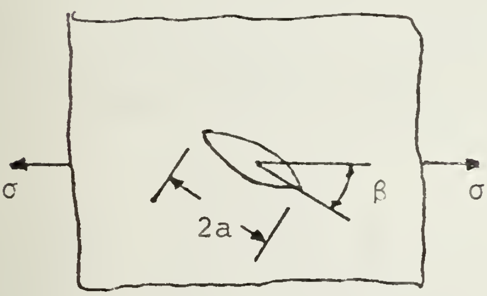
$\lambda = 3.4\nu$ (for plane strain)

CASE 5: Curved crack in equal bi-axial stress field.



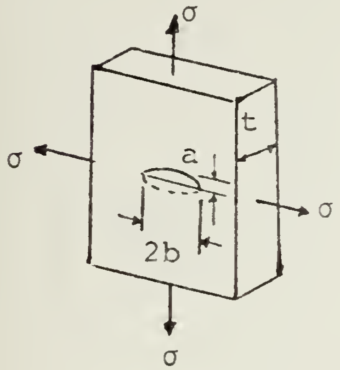
$$K_1 = \frac{\sigma(\pi R)^{\frac{1}{2}}}{(1+\sin^2\frac{\alpha}{2})} \left(\frac{\sin\alpha \;(1+\cos\alpha)}{2}\right)^{\frac{1}{2}}$$

CASE 6: Inclined crack in uniform tension in infinite sheet.



$$K_1 = \sigma \sin^2\beta\sqrt{\pi a}$$

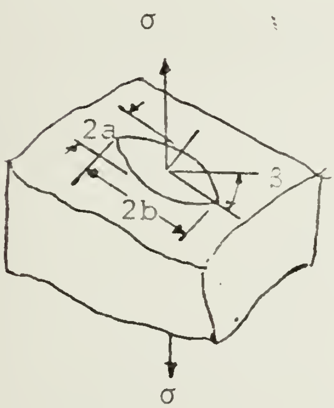
CASE 7: Semi-elliptical surface crack in plate subject to general extension.



$$K_1 = [1+.12(1-\frac{a}{b})]\frac{\sigma\sqrt{\pi a}}{\phi_o}(\frac{2t}{\pi a}\tan\frac{\pi a}{2t})^{\frac{1}{2}}$$

$$\phi_o = \int_o^{\frac{\pi}{2}} [1-(\frac{b^2-a^2}{b^2})\sin^2\theta]^{\frac{1}{2}}d\theta$$

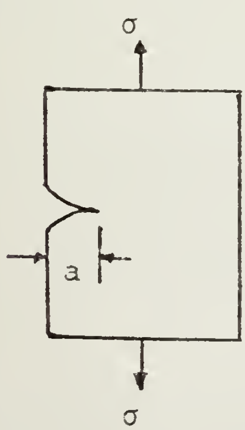
CASE 8: Elliptical crack in infinite body subject to uniform tension.



$$K_1 = \frac{\sigma\sqrt{\pi a}}{\phi_o}(\sin^2\beta+\frac{a^2}{b^2}\cos^2\beta)^{\frac{1}{4}}$$

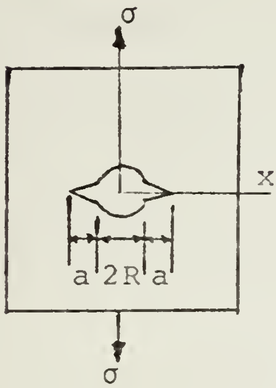
$$\phi_o = \int_o^{\frac{\pi}{2}} [1-(\frac{b^2-a^2}{b^2})\sin^2\theta]^{\frac{1}{2}}d\theta$$

CASE 9: Edge crack in a semi-infinite sheet in plane tension.



$$K_1 = 1.12\ \sigma\sqrt{\pi a}$$

CASE 10: Double crack emanating from a hole in a plate.



$$K_1 = \sigma\sqrt{\pi a}\ \sqrt{1+R/a}\ [1-\frac{2}{\pi}\{\sin^{-1}$$

$$\frac{R}{R+a} - \frac{R}{R+a}[1+\frac{R^2}{(R+a)^2}]$$

$$\sqrt{1-R^2/(R+a)^2}\}]$$

APPENDIX B

A summary of data on the K_{1scc} values for selected steels and welds is given in Figures B-1 to B-4.[59] In some of the figures, the values for K_{1c} are also shown for comparison. K_{1c} data is denoted by the symbol □. The symbol △ is used to indicate K_{1x} values. K_{1x} is a term which is used to represent approximate fracture toughness data.

In Figure B-5,[59] the K_{1scc} envelopes for the same steels and welds are superimposed upon each other. The straight lines in the figure indicate how the K_{1scc} values relate to the maximum depth of long thin surface flaws which can be tolerated without crack growth.

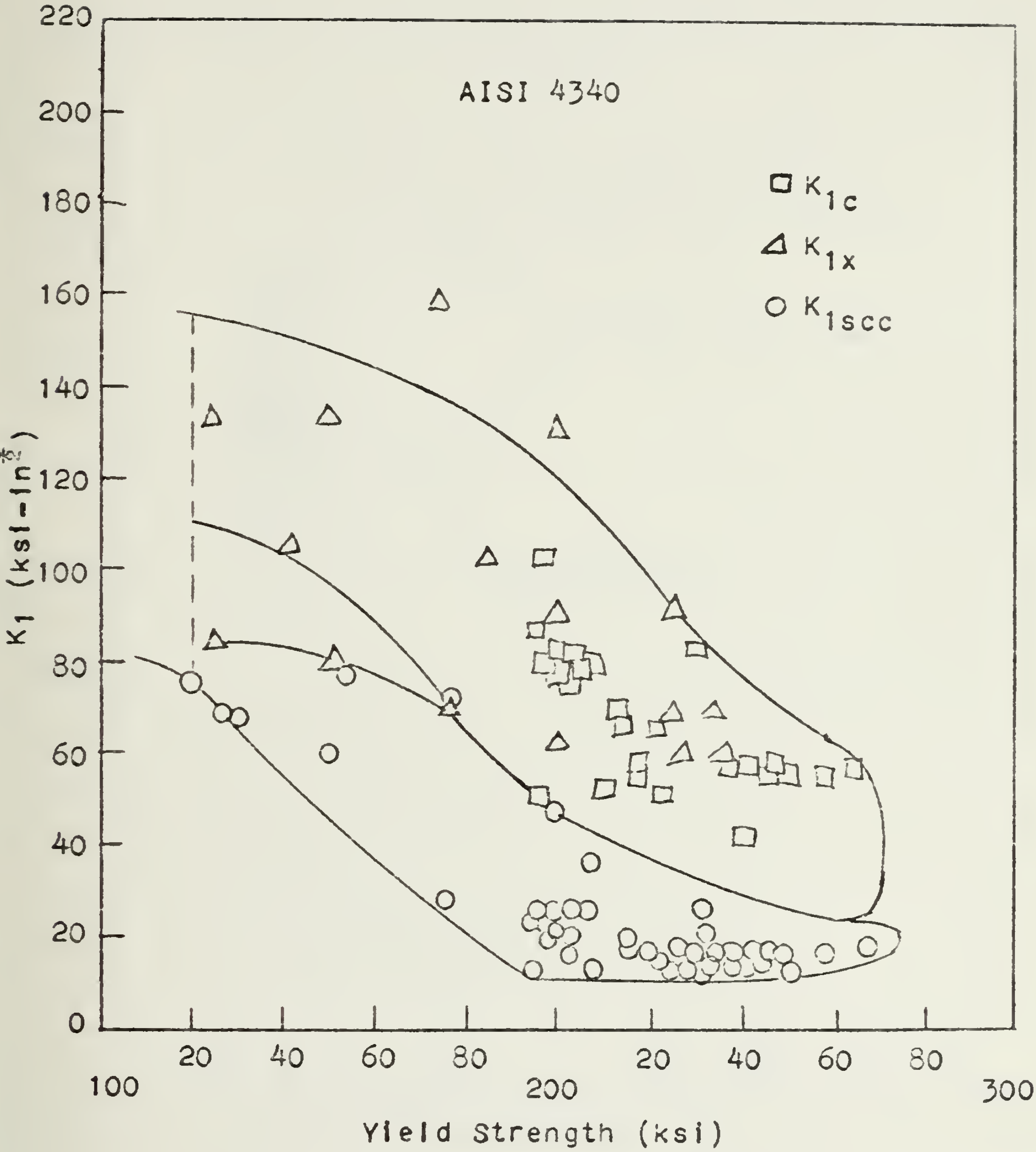


FIGURE B-1. Stress corrosion resistance and fracture toughness of AISI 4340 steel.

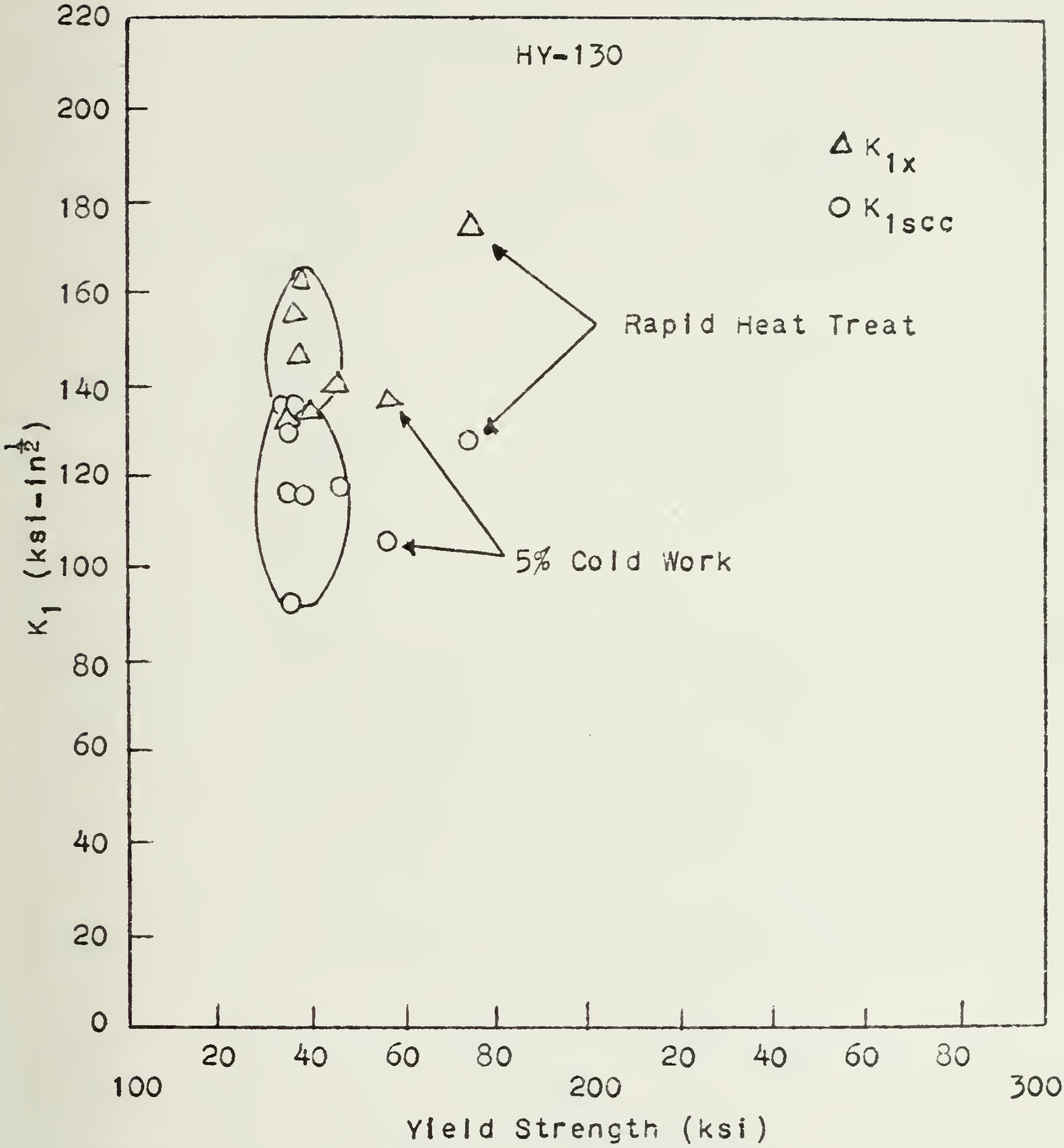


FIGURE B-2. Stress corrosion resistance and fracture toughness of HY-130 steel.

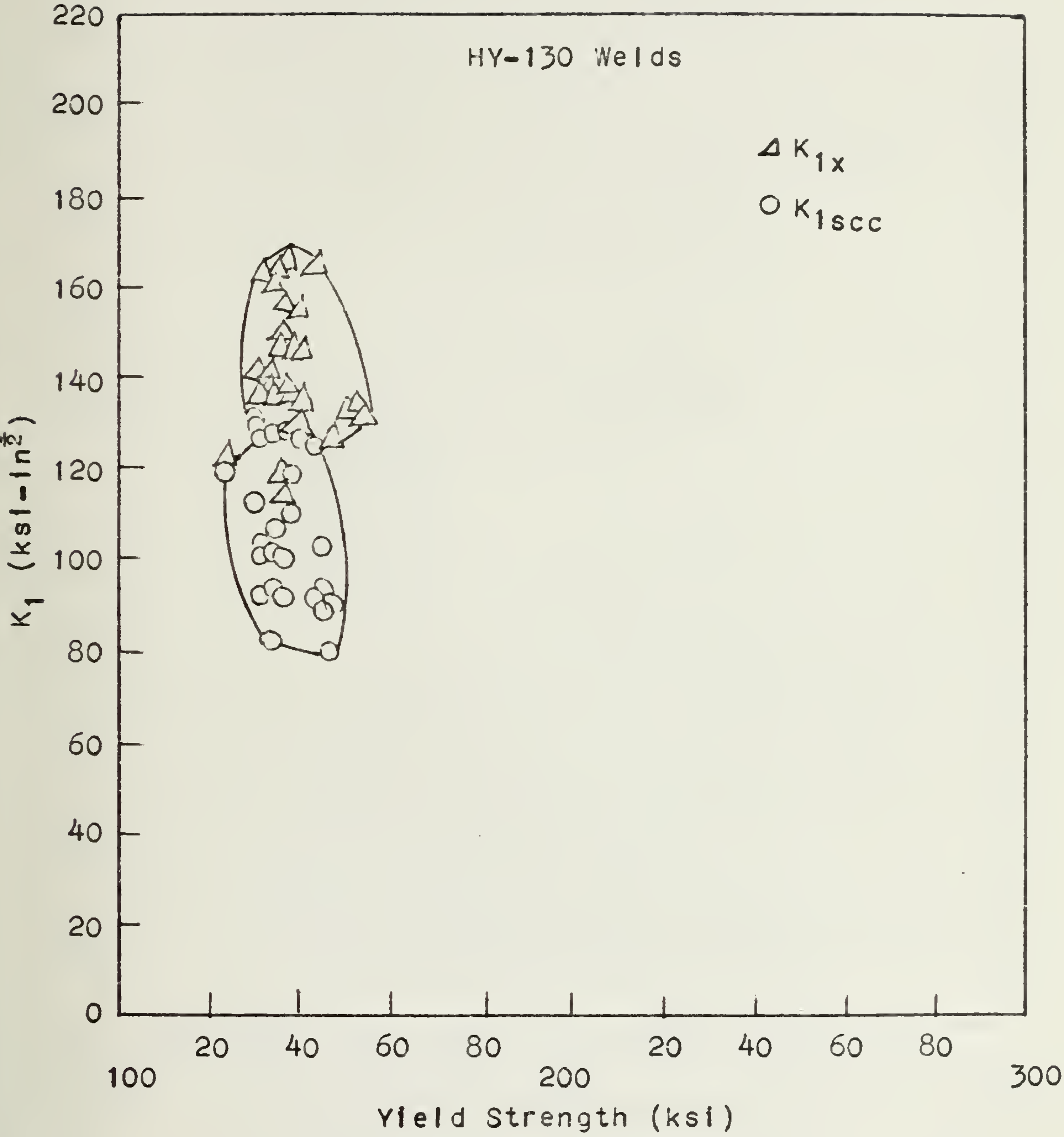


FIGURE B-3. Stress corrosion resistance and fracture toughness of HY-130 steel weldments.

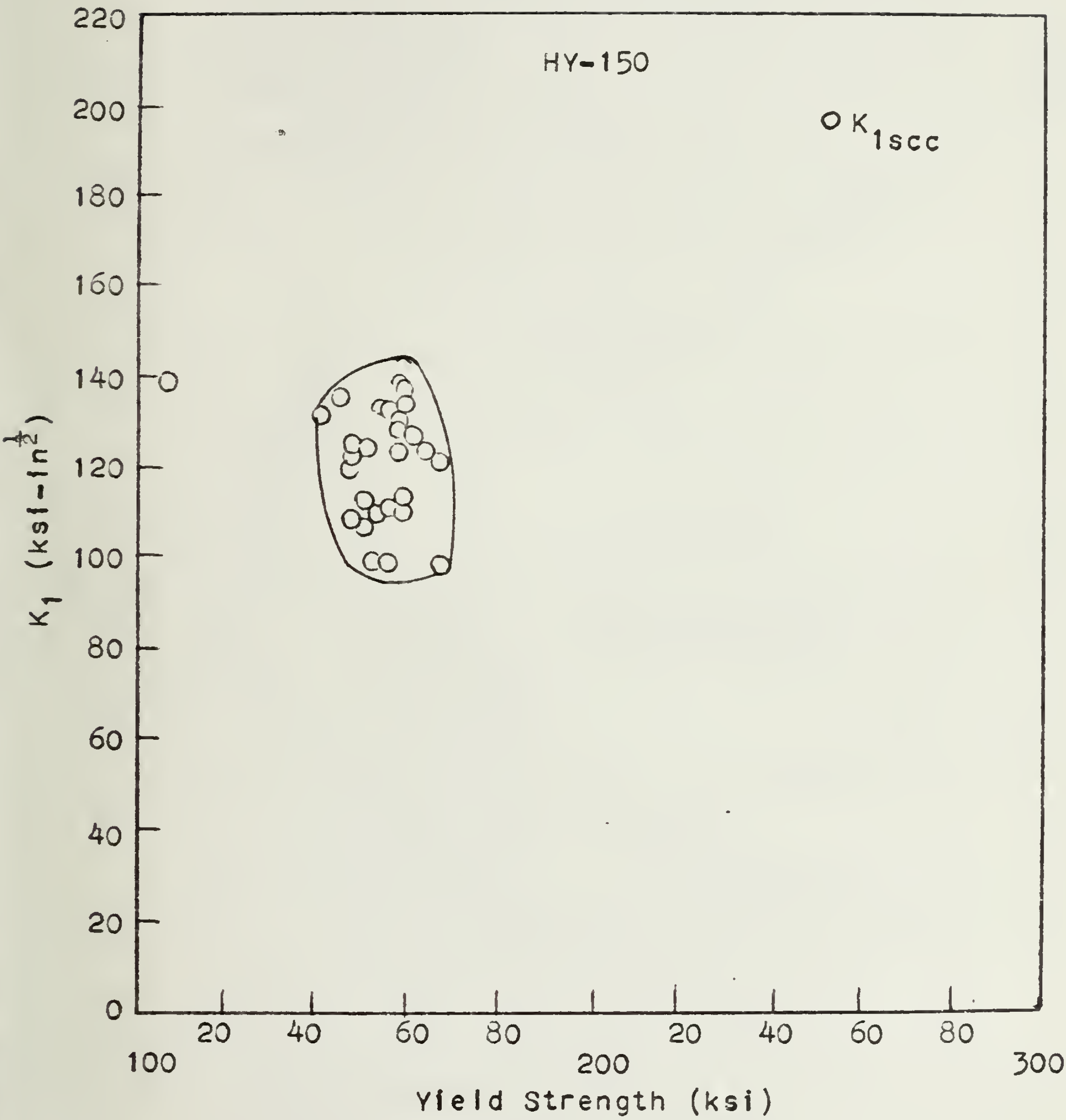


FIGURE B-4. Stress corrosion resistance and fracture toughness of HY-150 steel.

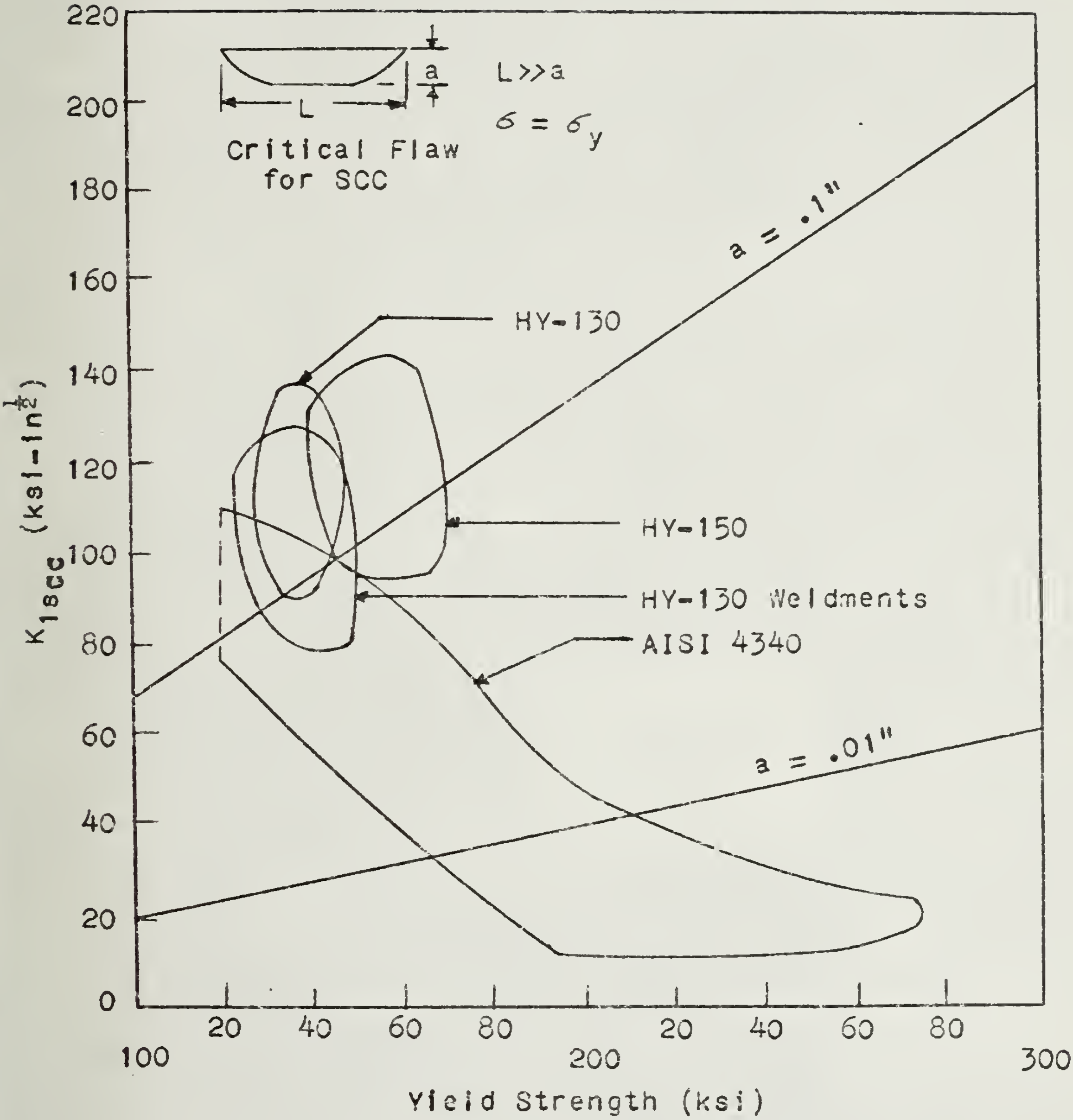


FIGURE B-5. Envelopes of K_{1scc} values.